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MILITARY STANDARD

PHOTOGRAPHIC LENSES



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MIL-STD-150A

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1. SCOPE

1.1 PURPOSE. This standard is issued for the purpose of establishing uniform definitions, nomenclature, classification of defects, methods of testing, and measurements pertaining to the field of photographic lenses. An appendix, containing nonmandatory reference material, is provided for use in the preparation of specifications and other procurement documents.

1.2 CLASSIFICATION. This standard covers photographic lenses typed according to their use. The keywords are italicized for convenient reference.

- I *Aerial Reconnaissance.* A type I lens shall be suitable for use in aerial reconnaissance. It will be used at or near infinity focus and usually will have low distortion and a flat field.
- II *Aerial Mapping.* A type II lens shall be suitable for use in accurate aerial mapping. It will be used at or near infinity focus and usually will have a flat field. The distortion characteristics in this type of lens are usually designated and controlled within precise limits.
- III *General Photographic.* A type III lens shall be suitable for use in view camera and hand-held still cameras. It will be used to photograph both near and distant objects.
- IV *Process.* A type IV lens shall be suitable for use in photolithography, process work, and precise reproduction from flat copy. It will be used at or near unity magnification. In this type of lens, lateral and longitudinal chromatic aberration, secondary spectrum, and distortion are corrected to a high degree.
- V *Motion Picture Camera.* A type V lens shall be suitable for use in motion picture cameras. It will be used to photograph both near and distant objects. A type V lens differs from a type III lens in that it usually is of shorter focal length and smaller field of view.
- VI *Enlarger.* A type VI lens shall be suitable for use in photographic enlargers. It will be used at finite magnifications, will usually have low color aberrations, and in certain applications distortion characteristics will be designated and controlled within precise limits.
- VII *Projection.* A type VII lens shall be suitable for use as an objective lens in motion picture, film strip, opaque, slide, and overhead projectors. It will be used at finite magnification and will have a flat field. This type of lens usually differs from a type VI lens in that it is faster, covers a smaller field of view, and has less correction of aberrations.
- VIII *Photomicrographic.* A type VIII lens shall be suitable for use in photomicrography. It will be used with the object at the shorter conjugate.
- IX *Portrait.* A type IX lens shall be suitable for use in portrait photography. It will be used to photograph both near and distant objects. It usually differs from a type III lens in having less correction of aberrations.
- X *Viewfinder.* A type X lens shall be suitable for use in viewfinders.
- XI *Condenser.* A type XI lens shall be suitable for use in condensers. It

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will be used for the collection and distribution of radiation in projection and enlarging systems.

XII Copying. A type XII lens shall be suitable for use in reproduction from flat copy. It will be used at or near unity magnification. It usually differs from a type IV lens in that it has greater lens speed and less correction of aberrations.

XIII Microphotographic. A type XIII

lens shall be suitable for use in microfilming and microcopying. It usually will be used at magnifications between 0.1 and 0.024.

XIV Recording. A type XIV lens shall be suitable for use in recording instruments or fluorescent screen presentation. It will be used at a finite magnification and generally will be of a special design to meet the specific requirements.

2. REFERENCED DOCUMENTS

2.1 NOT APPLICABLE.

3. DEFINITIONS

3.1 AXES, POINTS, AND DISTANCES.

3.1.1 Optical axis. The optical axis of a perfect lens or lens combination is that continuous straight line in space which passes through all of the centers of curvature of the various spherical optical surfaces, coincides with the axes of rotational symmetry of nonspherical surfaces and is perpendicular to flat surfaces.

3.1.2 Axis of best definition. The axis of best definition of a lens is that line in which is perpendicular to the plane of best definition and passes through the principal focus.

3.1.2.1 Plane of best definition. The plane of best definition is that plane in the image space which contains those images representing a compromise of quality selected as best for the purpose for which the lens is intended.

3.1.2.1.1 Plane of best average definition over the picture area. The position of focus giving the highest area weighted average resolution (AWAR) will be first considered as the position of best average definition

over the picture area, or BADOPA. In case the resolving power for the axial image point is less than the AWAR, the position of focus at which the axial resolving power equals the AWAR will be considered the position of BADOPA.

3.1.2.1.2 Field tilt. A lens field tilt when its best image plane is tilted with respect to the mounting shoulder for the lens. This effect is usually caused by slight amounts of decentering or tilt in or within a member of an optical system. Field tilt results in a lack of symmetry of resolution in the field of the lens about the axis. Usually the points of greatest asymmetry lie along a diagonal of the picture format. The limits for field tilt may be specified in terms of maximum focus difference between the two positions of best focus at a specified angle during the diagonal exhibiting the greatest asymmetry.

3.1.2.2 Best principal focus. The best principal focus of a lens is the point of intersection of the lens axis with the plane of best definition from an incident beam of parallel light perpendicular to this plane.

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3.1.2.2.1 When a lens is supplied in cells, without barrel or shutter, the locating surface of the lens mount is defined as the seating surface of the rear cell.

3.1.3 Mechanical axis. The mechanical axis of a lens is that continuous straight line in space perpendicular to the plane of the flange or locating surface of the lens mount and passing through the center of symmetry of the flange or locating surface.

3.1.3.1 Flange tilt. The flange tilt of a lens is the angle between the optical axis and the mechanical axis.

3.1.3.2 Plane of the receiver. The plane of the receiver is that plane in the image space in which the receiver or the film in a camera is located.

3.1.3.2.1 Focal tilt. The focal tilt is the angle between the plane of best definition and the plane of the receiver due to the mechanical structure between the lens flange and the receiver. It is not a true characteristic of the lens alone.

3.1.4 Equivalent focal length.¹ The equivalent focal length, or EFL, often referred to more simply as the focal length, determines the scale of the image produced by the lens. When a given object is at an infinite distance, images produced by distortionless lenses of the same equivalent focal length will be equal in size, and images produced by lenses of different equivalent focal lengths will vary in size directly as the respective equivalent focal lengths. The equivalent focal length is defined by the equation:

$$\text{EFL} = \frac{7'}{\tan \beta} \quad (1)$$

$\beta = 0$

where $7'$ is the transverse distance from the principal focus to the center of the image in the image-space focal plane of an infinitely distant object point which lies in a direction making an angle β with the optical axis. The equivalent focal length shall be measured in accordance with 5.1.2.2.

3.1.5 Calibrated focal length.² The calibrated focal length, or CFL, is defined as an adjusted value of the equivalent focal length of a lens mounted in a camera or cone, so chosen as to distribute the distortion in the manner best suited to conditions under which the photograph is to be employed. The calibrated focal length shall be determined in accordance with 5.1.2.3. The calibration conditions shall be covered by the detailed specification.

3.1.6 Back focal distance. The back focal distance, or BF, is defined as the distance measured from the vertex of the back surface of the lens to the plane of best definition. The back focal distance shall be measured in accordance with 5.1.2.4.

3.1.7 Flange focal distance. The flange focal distance, or FD, is defined as the minimum distance from the center of symmetry of the lens flange in the plane of the flange to the plane of best definition. In a perfect lens, this distance is measured along the mechanical axis which coincides with the axis of best definition. The flange focal distance shall be measured in accordance with 5.1.2.5.

3.1.8 Front focal distance.² The front focal distance, or FF, is defined as the distance measured from the principal focus located in the front space to the vertex of the front surface. The front focal distance shall be measured in accordance with 5.1.2.6.

3.1.9 Front vertex back focal distance.³ The

¹ American Standard Method of Designating and Measuring Focal Lengths and Focal Distances of Photographic Lenses. Z39.4-21-1948

² See footnote 1, page 6.

³ See footnote 1, page 6.

front vertex back focal distance, or FVD, is defined as the distance measured from the principal focus in the back space to the vertex of the front surface. The front vertex back focal distance shall be measured in accordance with 5.1.2.7.

3.1.10 Telephoto ratio. The telephoto ratio is defined as the direct ratio of the equivalent focal length to the front vertex back focal distance.

3.1.11 Depth of focus and depth of field. For every plane in the object space, a photographic lens produces an image plane of best definition in the image space. In front of or behind this plane of best definition is a region within which the images of the selected object plane are of satisfactory quality. The distance separating the focal planes bounding this region is the depth of focus for the selected object plane. Similarly, there exists a region in space within which objects are imaged with satisfactory quality on a selected image plane. The distance separating the planes bounding this region is the depth of field. The extent of these regions of satisfactory focus may be defined in terms of a 10 percent reduction of area weighted average resolution (AWAR) below that obtained at the best focal position.

3.2 APERTURE AND RELATED QUANTITIES.

3.2.1 Lens speed. Lens speed is that property of a lens which affects the image illuminance. Lens speed shall be specified in terms of the following expressions: aperture ratio, relative aperture, or T-stop.

3.2.2 Aperture ratio.⁴ The aperture ratio is the ratio 1:N or the fraction 1/N (written in this manner with the first member of the ratio, or the numerator of the fraction,

equal to 1) where N is defined by the equation:

$$N = \frac{1}{2n \sin \alpha}$$

In this formula, n is the index of refraction of the medium in which the image is formed (approximately 1, if the image is formed in the air) and α is the angle subtended at the axial point of the image by the semidiameter of the exit pupil of the lens at a given diaphragm setting. If the exit pupil is not circular, the equivalent circle having the same area as the actual exit pupil should be used. Thus, for an objective in air, the aperture ratio is equal to $2 \sin \alpha$. If the aperture ratio is given without qualification, its value is that corresponding to the largest indicated diaphragm opening and an infinitely distant object. If the object is at a finite distance, the value of the aperture ratio should be qualified by a statement of the corresponding magnification. The aperture ratio is applicable for the determination of exposure time when the object is at an infinite or a finite distance. For any magnification, the exposure time is inversely proportional to the square of N. Thus, the aperture ratio is a measure of the image illuminance. (For test procedure see 5.1.2.8).

3.2.3 Effective aperture.⁵ The effective aperture of a photographic objective for distant objects, for a given setting of the diaphragm, is an opening equivalent to a right section of the largest beam of parallel light from an axial object point that is transmitted by the lens. It is usually circular, or approximately so, and is specified by its diameter. If the section is not circular, the effective diameter shall be the diameter of a circle having the same equivalent area. (For test procedure, see 5.1.2.9.)

3.2.4 Clear aperture.⁶ The clear aperture of each surface in a lens system is the maxi-

⁴ American Standard Methods of Designating and Measuring Apertures and Related Quantities Pertaining to Photographic Lenses, Z38.4.20 — 1948

⁵ See footnote 4, page 9.

imum clear opening of the surface which is actually used in forming an image in any part of the field. The mount aperture at each surface shall be at least as large as the clear aperture in order that vignetting will not exceed the computed value. The clear aperture is usually circular and specified by its diameter. It is sometimes referred to as the free aperture.

3.2.5 Relative aperture.⁵ The relative aperture shall be defined as the ratio of the EFL to the diameter of the effective aperture. The symbol for relative aperture shall be $f/$ followed by a numerical value. It is written as a fraction, for example, $f/2$ signifies that the diameter of the effective aperture is one-half the focal length. For an object at an infinite distance, the denominator of the relative aperture and the second member, N , of the aperture ratio are identical, provided the image is formed in air and the imagery obeys the sine condition.

3.2.5.1 f -number.⁶ The f -number shall be defined as the denominator in the expression for the relative aperture. Thus, if the relative aperture is $f/2$, the f -number is 2.

3.2.6 T-stop and T-number.⁷ The T-stop is referred to as the aperture of a lens calibrated photometrically and assigned a T-number, which is the f -number of a circular opening in a fictitious lens having 100 percent transmittance, and which gives the same central image illuminance as the actual lens at the specified stop opening. Hence, for a lens with a circular aperture, the

$$\text{T-number} = \frac{\text{f-number}}{\sqrt{t}} \quad (3)$$

where t is the transmittance. For a lens with an effective aperture of any shape and area

⁵ See footnote 4, page 9.

⁶ See footnote 4, page 9.

⁷ American Standard, Aperture Calibration of Motion Picture Lenses PH22.90 — 1953.

A, the corresponding formula is:

$$\text{T-number} = \frac{f}{2} \sqrt{\frac{\pi}{At}} \quad (4)$$

The transmittance of the lens shall be defined as the ratio of the transmitted light flux to the incident light flux. The symbol for the T-stop shall be T followed by a space and a numerical value — for example, T 2. The numeral 2 represents the T-number. (For test procedure, see 5.1.2.10.)

3.2.6.1 Area weighted average T-number. The T-number as defined in 3.2.6 is a comparative measure of illuminance on the axis of a lens. Since the illuminance usually varies over the field, a need may exist for determining T-numbers for off-axial image points and computing an average T-number. In accordance with the basic photometric relationships involved, the general definition of T number is given as

$$T_i = \frac{1}{2} \sqrt{\pi B/E_i} \quad (5)$$

Since, in accordance with this definition,

$$\frac{1}{2} \sqrt{\pi B} = T_i \sqrt{E_i}$$

$$T_i = T_o \sqrt{\frac{E_o}{E_i}} \quad (6)$$

In these expressions, T_i is the T-number for an image point in a zone i , T_o is the axial T-number, B is the object luminance, E_o is the illuminance on the axis, and E_i is the average illuminance for the zone. Compatible units should be used for quantities B , E_o , and E_i . When the illuminance is averaged over the field, weighting the average by the area of the circular zone in which the illuminance is determined, and this average is substituted for E_i in equation (6), the resulting T-number is called the area weighted average T-number, or AWAT. For circular zones which extend beyond the boundaries of the

picture format, only the area lying within the format shall be used in determining the weighting ratios. The equations for computing AWAT are:

$$AWAT = T. \left/ \sqrt{\sum \frac{A_i E_i}{A E_o}} \right. \quad (7)$$

$$\text{or } AWAT = 10 T. \left/ \sqrt{\sum \frac{A_i}{A} \sigma_i} \right. \quad (8)$$

in which A is the total area of the picture format, A_i is the area of a particular zone, and σ_i is the average relative illuminance for that zone expressed in percent.

3.2.7 Front operating aperture. The front operating aperture is defined as the limiting aperture at the front of the lens. It will usually be given as the maximum diameter of the entrance cone at the front vertex for the specified field of view at infinity focus.

3.2.8 Rear operating aperture. The rear operating aperture is defined as the limiting aperture at the rear of the lens. It will usually be given as the maximum diameter of the emergent cone at the rear vertex for the specified field of view at infinity focus.

3.3 CONSTRUCTIONAL FEATURES. Pertinent features include details of the construction of the lens. These may relate to the physical configuration, or arrangement of the individual elements, to some specified optical characteristic or to the nomenclature of the various parts. Constructional features of photographic lenses are listed with definitions and explanatory data.

3.3.1 Optical system.* The optical system includes all the parts of a photographic lens and accessory optical parts which are designed to contribute to the formation of an image on the photographic emulsion or on a screen for viewing.

3.3.2 Member.* A member of a photographic lens is a group of parts considered as an entity because of the proximity of its parts or because it has a distinct but not always entirely separate function.

3.3.3 Component.* A component of a photographic lens is a subdivision of a member. It may consist of two or more parts cemented together or with near and approximately matching surfaces.

3.3.4 Element.* An element of a photographic lens is a single uncompounded lens, i.e., a part constructed of a single piece. The total number of elements is a significant constructional feature of a lens.

3.3.5 Front of photographic lens.* The front of a photographic lens, in general, is the end carrying the engraving, and usually facing the longer conjugate. In lens drawings, the front generally faces left or up. A notable exception is certain lenses intended to be used in photomicrography in which the front of the lens faces the shorter conjugate.

3.3.6 Back of photographic lens.* The back of a photographic lens, in general, is the end carrying the mounting thread or other attaching means and usually facing the shorter conjugate.

3.3.7 Name of design. Designs of lenses in which particular configurations of elements are employed are often given names. These names are usually trade names, and the name ordinarily applied to any particular configuration is usually the trade name of the oldest design of a particular type such as "Tessar." In some cases, however, the design name may not be a trade name but may be based on some feature of the lens configuration such as "Symmetrical."

3.3.8 Telephoto. A telephoto lens is defined

* American Standard Nomenclature for Parts of a Photographic Lens PH3.25 - 1948.

* American Standard Nomenclature for Parts of a Photographic Lens PH3.25 - 1948.

as a lens for which the telephoto ratio is greater than one. (See 8.1.10.)

3.3.9 Glass types. A constructional feature is the type of optical glass of which each element is made.

3.4 MECHANICAL AND STRUCTURAL FEATURES.

3.4.1 Cell. A cell is a mechanical structure holding an element, component, or member.

3.4.2 Barrel. A barrel is a mechanical structure in which the lens is mounted.

3.4.3 Cone. A cone is defined as the mechanical structure to which a lens barrel or shutter, with lens, is attached in order to bring the image in focus in the film plane of a specific aerial camera.

3.4.4 Lens diaphragm. A lens diaphragm is a mechanical device for reducing the effective aperture of a lens. It may take the form of an iris or a Waterhouse stop. An iris diaphragm consist of leaves providing an opening continuously variable in size. A Waterhouse stop is a removable aperture of fixed size which fits in the lens barrel. Waterhouse stops are usually provided in a graded series of apertures.

3.4.5 Iris diaphragm control.* Unless otherwise specified, when looking at the front of a lens or remote control knob, a counter-clockwise rotation of the diaphragm control shall reduce the aperture or stop the lens down.

3.4.6 Parfocalized. Lenses mounted in barrels may be specified as parfocalized, i.e., the flange focal distance may be specified to close tolerances that would secure an image in satisfactory focus when the lenses are interchanged on a camera.

* American British-Canadian Air Standardization Agreement, Air Camera Lens Diaphragm Rotation and Lens Speed Rating System. ABC AIR STD 52/2, 5 Feb 54.

3.4.7 Spanner wrench openings. When required in order to facilitate removal of cells, elements, components, or members from a cell or barrel, there shall be two openings 180 degrees apart for application of a spanner wrench. Each opening shall either be circular in shape, or a slot with parallel sides.

3.5 FIELD OF VIEW. The field of view of a lens is a measure of the size of the image area or conjugate object area which is satisfactorily reproduced. This field may be defined in terms of the maximum size of the negative or projection material with which the lens is to be used.¹⁰ The angular measure for field of view is the half angle, which, unless otherwise specified, is the angle subtended at the first nodal point by the optical axis and a straight line to an object point which is imaged at the extreme corner of the negative. For a projected image, the half angle is the angle subtended at the second nodal point by the optical axis and a line to the image point conjugate with the extreme corner of the projection material. The half angle is sometimes referred to the side of the image area and in such cases it shall always be so specified. The field of view may also be designated as the total field angle which is twice the half angle. Coverage is a less precise term for field of view.

3.6 OPTICAL CHARACTERISTICS. Optical characteristics include all properties of a lens affecting its optical performances such as image quality, distortion, transmittance, image color, and condenser characteristics. When specifying optical characteristics or individual aberrations, the definitions and nomenclature set forth herein shall be used.

3.6.1 Image quality. Image quality embraces

¹⁰ Format Sizes for Air Cameras. ABC AIR STD 52/1, 5 Feb 54. The participants agreed that air camera format sizes shall be: 2 1/4 by 2 1/4 inches, 4 1/2 by 4 1/2 inches, 9 by 9 inches, 9 by 18 inches, 18 by 18 inches. Format Sizes for Ground Cameras. ABC AIR STD 52/2, 15 Mar 54. Ground camera format sizes standardized shall be: 1 by 1 1/2 inches (24 by 36 millimeters), 2 1/4 by 2 1/4 inches, 2.2 by 2.75 inches.

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es all the properties of a lens affecting the quality of the image such as resolving power, aberrations, image defects, and veiling glare. Aberrations are optical defects inherent in the lens design. Because of manufacturing variations, it often happens that the measured aberrations differ from the computed aberrations. Image defects are optical defects not inherent in the lens design and resulting entirely from manufacturing and mounting variations. This standard is primarily concerned with optical performance. Optical performance can be measured in terms of resolving power, or specific optical characteristics.

3.6.2 Resolving power. The resolving power of a lens is a measure of its ability to image closely spaced objects so that they are recognizable as individual objects. The resolving power shall be expressed in lines per millimeter, usually in the short conjugate plane. Resolving power is measured by photographing or observing suitable test charts at specified angular distances from the center of the field. The test charts shall consist of groups of parallel straight lines and spaces of equal width; the resolving power is the reciprocal of the center-to-center distance of the lines that are just distinguishable in the recorded image. By "just distinguishable" is meant that the observer is able to count the correct number of lines in the recorded image, over the entire length of the lines and in the correct orientation, subject to the provision that no coarser pattern shall be unresolved. The appearance of resolution in a finer pattern after failure to resolve a coarser pattern is an indication of the presence of spurious resolution. Spurious resolution is a phenomenon wherein fine lines are resolved, yet coarse lines are not. For non-axial points, it is necessary to consider the orientation of the lines. For example, the resolving power for radial lines, or "radial resolving power" (sometimes called "sagittal resolving power"), at a given point in the

image plane is the resolving power for closely spaced lines that are parallel and adjacent to the radius drawn from the center of the field to the given point. Resolving power for tangential lines, or "tangential resolving power," is the resolving power for closely spaced parallel lines that are tangent and adjacent to a circle drawn through the given point whose center lies at the center of the field. Resolving power may be specified as minimum acceptable resolving power, regardless of whether radial or tangential at specified angles from the optical axis of the lens, or it may be specified at both minimum acceptable radial and minimum acceptable tangential resolving power at specified angular distances from the optical axis. The average resolving power weighted in terms of the area of the negative, the area weighted average resolution (AWAR), provides a single value by which the resolving power for the entire field may be specified. (See 3.1.2.1.1 and 3.6.2.5.)

3.6.2.1 Photographic resolving power. Photographic resolving power is used in specifying and measuring performance of type I, II, III, IV, V, IX, XII, and XIII lenses and is the greatest number of lines per millimeter recorded photographically as separate lines. A target pattern is considered resolved when it meets the conditions described in 3.6.2. Photographic resolving power depends markedly on the photographic conditions employed, and on the presence of background glare from the illuminated target. When specifying photographic resolving power, it is necessary also to specify the color of light to be used, the type of photosensitive material and processing, the lens speed at which the test is made, the contrast of the target, and the magnification or focus at which the lens is tested. (See 5.1.2.12.1)

3.6.2.2 Visual resolving power. Visual resolving power is used in specifying and measuring of type X lenses, and is defined as the greatest number of lines per milli-

meter in the image of a test target pattern that are just barely distinguishable as separate lines under adequate magnification. When specifying visual resolving power it is necessary also to specify the target contrast. (See 5.1.2.12.2.)

3.6.2.3 Projected photographic resolving power. Projected photographic resolving power is used in specifying and measuring the performance of type VI lenses and is defined as the greatest number of lines per millimeter, in the object plane, that are barely distinguishable as separate lines when observing under magnification a photographically recorded, projected image of a suitable test target. (See 5.1.2.12.3.) When specifying projected photographic resolving power it is necessary also to specify lens speed, focus, magnification, type of illumination, contrast of target, type photosensitive material and its processing.

3.6.2.4 Projected visual resolving power. Projected visual resolving power is used in specifying and measuring the performance of type VII lenses and is defined as the greatest number of lines per millimeter in the object plane that are distinguishable as separate lines in the projected image. When specifying projected visual resolving power, it is usually understood to imply a high contrast target (dark lines on light background). (See 5.1.2.12.4.)

3.6.2.5 Area weighted average resolution. A single average value for the resolution over the picture format may be determined for any given focal plane as the area weighted average resolution, or AWAR. To determine the AWAR, the picture format is divided into concentric annular zones whose boundaries are determined from the angles which are midway between successive test angles. For zones which extend beyond the boundaries of the picture format, only the area lying within the format shall be used in determining the weighting ratio. The reso-

lution obtained at any given test angle is multiplied by the ratio of the area of the zone for that angle to the total area of the picture format. The AWAR is the sum of these products. To obtain a single value of the resolution for each test angle, the geometric mean of the tangential and radial resolutions shall be used. However, the computations may be simplified by the use of an arithmetic mean whenever the tangential and radial resolutions differ by less than a factor of 2 to 1. When more than one measurement is made at any given test angle, an arithmetic mean shall be determined for the tangential and another for the radial resolutions. The area weighted average resolution is defined as:

$$AWAR = \sum \frac{A_i}{A} \sqrt{R_i T_i} \quad (9)$$

where A_i is the area of a particular zone, R_i is the average radial resolving power in this zone (or radial resolving power at the midpoint of the zone), T_i is the average tangential resolving power in the zone (or the tangential resolving power at the midpoint of the zone), and A is the total area of the picture format, and Σ is the summation sign, summing the values

$$\frac{A_i}{A} \sqrt{R_i T_i}$$

over all zones in the picture area.

3.6.3 Astigmatism and curvature of field. In general, a lens possesses two image surfaces: one in which lines radial to the optical axis are best defined and the other in which lines tangent to circles concentric with the axis are best defined. Noncoincidence of these two image surfaces is called astigmatism, and the separation of the two image surfaces, measured parallel to the optical axis, is called the astigmatic difference. A median surface lying between the two is called the surface of least confusion and the definition in this image surface is least affected

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by orientation of the object. None of the surfaces is a true plane. The departure of the surface of least confusion from a true plane is called curvature of field. Resolving power figures, specified in accordance with 3.6.2, will usually be considered as referring to a flat image and object plane. When curvature of field is specified, the magnification at which it is to be measured shall be stated. (See 5.1.2.13.) Figure 1 is plotted as an example of the astigmatic difference.

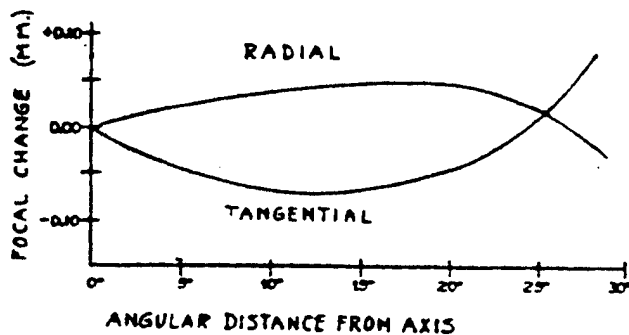


FIGURE 1. Astigmatic Difference

3.6.4 Color correction. Color correction is defined as the reduction of longitudinal and lateral chromatic aberrations. It may be specified in terms of the kind of light and color sensitivity of the photographic material to be used with the lens, e.g., the lens is color corrected for use with white light and panchromatic film of ASA speed 100. The color correction may be specified in terms of the Fraunhofer lines in the solar spectrum that are to be used in the lens calculations, e.g., C and F correction. The magnification at which the color correction is accomplished shall be designated. (See 5.1.2.14.)

3.6.4.1 Longitudinal chromatic aberration. Longitudinal chromatic aberration is defined as a variation in back focal distance for light of different colors or wave lengths. It is specified in terms of this focal change for light of specified colors. (See 5.1.2.14.1.) Figure 2 is plotted as an example of longitudinal chromatic aberration.

3.6.4.2 Lateral chromatic aberration. Late-

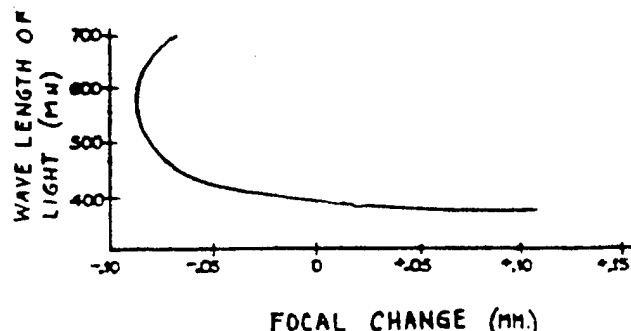


FIGURE 2. Longitudinal Chromatic Aberration

ral chromatic aberration is a variation in image scale of a lens for light of different colors or wave lengths. When required, limits on lateral chromatic aberration will be specified as the radial displacement in millimeters of the image in the first color from the image of the same point in the second color. (See 5.1.2.14.2.) Figure 3 is plotted as an example of lateral chromatic aberration.

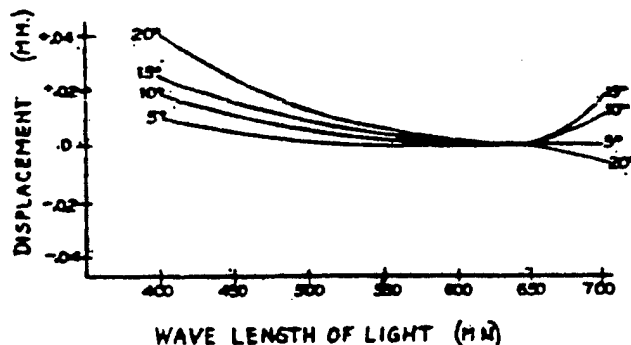


FIGURE 3. Lateral Chromatic Aberration

3.6.5 Magnification.

3.6.5.1 Paraxial magnification. The paraxial magnification, often referred to more simply as magnification, determines the scale of the image when the object is at a finite distance from the lens. The paraxial magnification, or PM, is defined by the following equation:

$$PM = \lim_{\gamma \rightarrow 0} \frac{\gamma'}{\gamma} \quad (10)$$

where γ' is the radial distance from the optical axis to the image point in the image plane

conjugate with the object plane, and γ is the radial distance in the object plane from the optical axis to the object point. Unless otherwise specified, the image plane is defined as the plane of best photographic imagery for the axial object point; the image plane may also be specified as the plane of best definition. Paraxial magnification shall be measured in accordance with 5.1.2.15.1.

3.6.5.2 Calibrated magnification. The calibrated magnification, or CM, is defined as an adjusted value of the paraxial magnification of a lens mounted in an instrument. This value is so chosen as to distribute the distortion in the manner best suited to the conditions under which the lens is to be employed. The calibrated magnification shall be determined in accordance with 5.1.2.15.2. The calibration conditions shall be covered by the detailed specification.

3.6.6 Distortion. These are two kinds of distortion—radial and tangential. When distortion is referred to without designation, radial distortion is implied. In some instances, it may be desirable to specify the distortion in terms of cartesian coordinates rather than polar coordinates. Because of the wider usage of the polar method of specifying distortion, radial and tangential distortion only are defined in this standard. This does not preclude the specification of distortion in cartesian coordinates. Small random distortions through the field may be introduced by inhomogeneities in the glass and irregularities in the surface of the elements. Figure 4 is plotted as an example of distortion.

3.6.6.1 Radial distortion. Radial distortion is a radial displacement of image points from the undistorted position, computed on the basis of the equivalent focal length or calibrated focal length when the object is at infinity, or on the basis of paraxial magnification or calibrated magnification when the

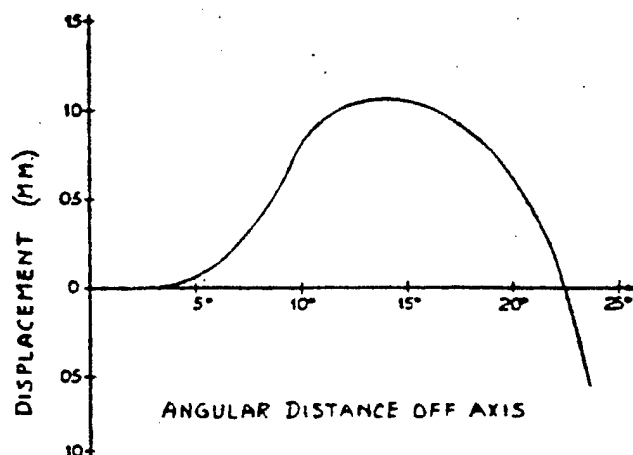


FIGURE 4. Distortion

object is at a finite distance from the lens. When radial distortion is present, straight lines in the object space not passing through the optical axis are reproduced as curved lines in the image. When the image point is displaced radially outward from the center of the image, the distortion is positive (commonly called barrel distortion if the absolute value of the negative distortion is continuously increasing from the center.) When the displacement of the image point is toward the center of the image, the distortion is negative (commonly called pincushion distortion if the absolute value of the negative distortion is continuously increasing from the center). The magnitude of the distortion and its tolerances shall be specified in millimeters. It may be specified in terms of the amount at different field angles, or by means of a curve, plotted in millimeters against the field angle. When limits to the tolerated distortion are specified, they shall be specified in millimeters and shall apply to any part of the field for which the lens is corrected. When specifying distortion, the conditions under which the lens is used, whether with parallel light, copying at 1 to 1 or 1 to 2, etc., shall be specified. (See 5.1.2.16.)

3.6.6.2 Tangential distortion. Tangential distortion is an image defect resulting in the displacement of image points (from the undistorted position) perpendicular to a radius

from the center of the field. The radius from which tangential distortion is measured originates at the principal point of autocollimation and contains the undistorted image point (the point at which the image would have fallen if it had not been distorted). When tangential distortion is present, straight lines in the object space which pass through the axis of best definition are reproduced as curved lines in the image. Tangential distortion is usually specified as a maximum permissible value throughout the field. (See 5.1.2.16.7.)

3.6.6.3 Errors of centration. Lenses with spherical surfaces are usually designed to be so constructed that the center of curvature of all the surfaces will lie on a single straight line termed the optical axis of the lens. If aspherical surfaces are used, their individual axes should correspond with the optical axis of the lens. Failures to comply with these conditions are termed errors of centration. Errors of centration cause tangential distortion, prism effect, field tilt, and asymmetric radial distortion.

3.6.6.4 Principal point of autocollimation. The principal point of autocollimation is a term used in measuring distortion and is defined exactly the same as principal focus, except that the plane of best definition is assumed to be the actual emulsion plane of the camera. (See 3.1.2.1.)

3.6.6.5 Prism effect. A lens has "prism effect" when light from an infinitely distant object point passing through the rear nodal point on a line perpendicular to the image plane of a camera is not imaged at the principal point of the perspective. The principal point of the perspective is the point of intersection with the focal plane of a perpendicular dropped from the rear nodal point of the lens. The principal point of the perspective and principal point of autocollimation should coincide. Decentered lenses behave as if they consisted of an ideal lens plus a thin prism.

The limits on prism effect, when required, shall be specified in terms of the vertex angle of the prism (index = 1.5) which would give the same result used in combination with a perfect lens. (See 5.1.2.17.)

3.6.7 Relative illumination. Relative illumination is defined as the ratio of the illuminance at the focal plane, for off-axis field positions, to the illuminance for the center of the field. This assumes that the luminance of the object field, as observed from the lens, is the same throughout the field, or that the field is a Lambert's law surface. The reduction in illuminance may be due to such causes as absorption, cosine variations, and barrel vignetting. Relative illumination shall be specified as percent of axial illuminance for image points at given angular distances. A curve on which percent of axial illuminance is plotted against field angle may be used. For purposes of specification, the following example is given: At $f/6.3$ the image illuminance at 45 degrees shall be no less than 8 percent, and at 35 degrees no less than 20 percent of the image illuminance on axis. (See 5.1.2.11.) Figure 5 is plotted as an example of relative illumination.

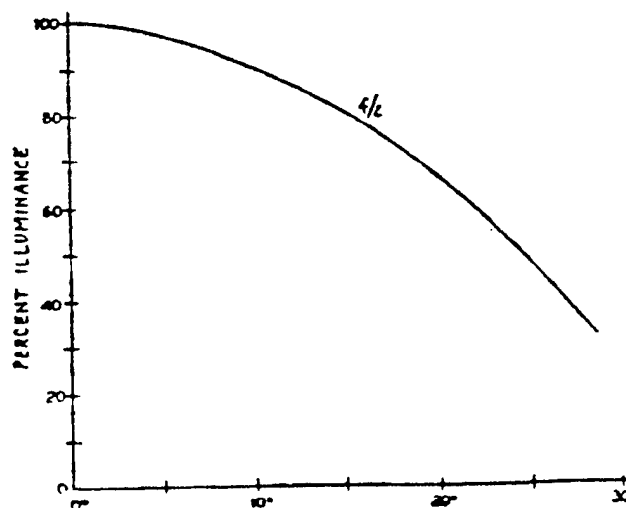


FIGURE 5. Relative Illumination

3.6.7.1 Vignetting. Vignetting is the progressive reduction in the cross-sectional area

of a beam of light passing through a lens as the obliquity of the beam is increased. It is due to obstruction of the beam by the various mechanical apertures, lens mounts, etc., within the lens. (The cross-section of the beam must be taken in a plane perpendicular to the optical axis of the lens.) Thus the beam of light from an axial object point passing through the lens is generally circular in cross-section, whereas an oblique beam originating at any extra-axial object point is generally non-circular in shape due to the "vignetting" action of the various limiting apertures within the lens. This restricted usage of the term "vignetting" must be carefully distinguished from its common meaning, which generally refers to the progressive reduction in image illuminance at increasing obliquity; the popular term thus combines the two distinct concepts of area vignetting and the \cos^4 effect.

3.6.7.2 *Cos⁴ law.* When light from a uniform diffusing source falls on a plane screen parallel with the source at a distance from it which is large in comparison with the dimensions of the source, the illuminance on the screen varies approximately as $\cos^4 \phi$, where ϕ is the angle between the axis of the source and the line joining the center of the source to the screen-point under consideration.

3.6.7.2.1 *Illuminance distribution.* When illuminated by an object of uniform luminance (viewed from the lens) and of a size sufficient to entirely fill the field of view, a lens having a circular diaphragm gives, within the mechanically unvignetted portion of the field, a distribution of illuminance which follows the \cos^4 law in terms of the obliquity angles at the diaphragm provided that the conditions stated below are satisfied. A lens with a diaphragm in front gives a distribution of illuminance proportional to $\cos^4 \phi$ (where ϕ is the obliquity angle in the object space) if the image is free from distortion and if the distance from the object

plane to the diaphragm is very large with respect to the diameter of the diaphragm. A lens with an internal diaphragm gives a distribution of illuminance proportional to $\cos^4 \phi_s$ (where ϕ_s is the obliquity angle in the diaphragm space) if the component behind the diaphragm does not contribute to the image distortion and the aperture is very small. A lens with a diaphragm behind it gives a distribution of illuminance proportional to $\cos^4 \phi'$ (where ϕ' is the obliquity angle in the image space) if the distance from the diaphragm to the image plane is very large with respect to the diameter of the diaphragm. In each case, the distribution of illuminance exactly corresponds to the distribution that would be obtained with a small circular Lambert's law source placed at such a distance from the image plane that the obliquity angles from the center of the source to the image points are as defined above.

3.6.7.2.2 *Variation of \cos^4 law.* Ordinary optical distortion in the lens will in general have a considerable effect on the distribution of illuminance across the field when expressed as a function of the entering obliquity angle ϕ . Some lenses have been constructed in which the $\cos^4 \phi$ law has been almost completely nullified by the presence of a sufficiently large amount of barrel distortion. Regarded naively, the distortion may be said to compress the outer part of the image, thus increasing the illuminance within it.

3.6.7.3 *Beam sections.* When it is necessary to compute the light distribution to be anticipated in a new lens design, or when estimating the light distribution from the dimensions of a lens without making actual photometric measurement, it is necessary to determine the section of a light beam as it enters or leaves the lens, at adopted reference planes perpendicular to the optical axis of the lens. Convenient reference planes are the planes defined by the rims of the lens mounts at the two ends of the lens barrel.

A light beam from an extra-axial object point, proceeding through the lens to its image point, will intersect these two reference planes in two "beam sections," generally non-circular in shape. These sections can be plotted and the areas measured (see 5.1.2.11.4), or they can be computed if the lens construction is known by tracing a sufficient number of skew rays.

3.6.7.4 Obliquity angles. For any point of the reference plane in the object space, ϕ is the angle between a normal from the front nodal point to the reference plane and a line joining that point with the object point. Similarly, for any point in the reference plane in the image space, ϕ' is the angle between the normal from the rear nodal point to the reference plane and a line joining that point with the image point. The obliquity angle ϕ is the same for every ray of the entering oblique parallel beam.

3.6.8 Transmittance. Lens transmittance is defined as the ratio of the light flux leaving a lens to the light flux entering the lens. It is specified as a percentage. When specifying percent transmittance and tolerance, the color of the light incident on the lens should be specified, and the spectral sensitivity of the film, when used, should also be specified. Percent transmittance may also be specified as spectral transmittance, wherein the transmittance at each wave length is specified.

3.6.8.1 Color contribution. For some uses the color of the light transmitted by an optical system is an important consideration. The color of the optical glass, coatings, interference films, and filters used determine this property. The effect that the optical system has upon spectral characteristics of the light flux entering the system is termed "color contribution." This property of an optical system is specified and measured in terms of conventional spectral transmittance curves, wherein transmittance in percent is plotted against wave length in m μ .

3.6.9 Spherical aberration. Spherical aberration is defined as an optical defect in which rays of light through different narrow annular zones of the lens (concentric with the optical axis) from an axial object point do not come to focus in the same plane. When required, the limits on spherical aberration may be specified as the difference in focal position for light through an annular zone of given width and radius and that for light through the axial zone of a radius approaching zero. It shall be negative when the focal distance for the zone of specified radius has the greater value. It may also be specified by means of a curve in which the focal difference is plotted against zone radius for different zones. When specifying spherical aberration, the color or wave length of light used and whether measured at infinite or at finite focus shall be specified. (See 5.1.2.18.) Figure 6 is plotted as an example of spherical aberration.

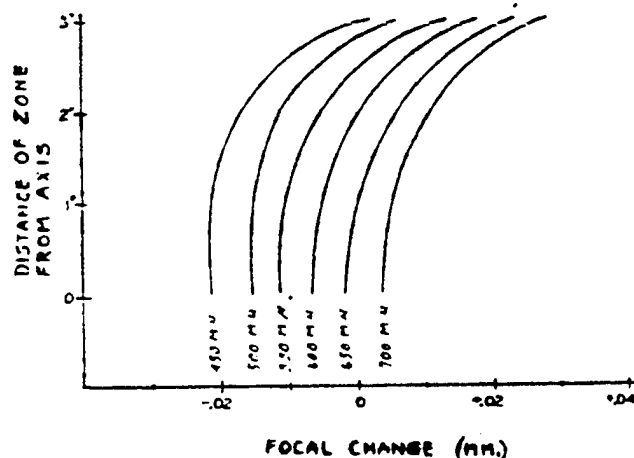


FIGURE 6. Spherical Aberration

3.6.9.1 Focal shift. Focal shift caused by spherical aberration is an important consideration. It may be specified as a change of focus either for the position of "greatest concentration" or for the "haze position" as the lens aperture is changed. It may also be specified as the difference in focus between these two positions at a given aperture.

3.6.9.1.1 Position of greatest concentra-

tion. The "position of greatest concentration" is defined as the focus position at which the aerial image, observed under magnification, shows the least amount of spreading. Very coarse resolution charts make a suitable object.

3.6.9.1.2 *Haze position.* The "haze position" is defined as the focus position at which is obtained the highest resolution even though there is considerable light around the image of the target. Haze position should be determined with a high contrast target.

3.6.10 *Veiling glare.*¹¹ Lenses in addition to focusing light to the image plane may scatter some light more or less widely over the image. This scattered light lowers the contrast of the image. The scattering may be due to a number of causes, such as dirt or scratches on the lens surface, multiple reflections from the surfaces, or reflections or scattering from mounts. This non-image forming light is referred to as "veiling glare." The measure of veiling glare is:

$$V = 100 \frac{E_g}{E_i} \% \quad (11)$$

where E_g is the image illuminance produced by the glare light, and E_i is the total image illuminance produced by image light plus glare light.

3.6.11 *Condenser characteristics.* A condenser, which may consist of one or more elements and components, is usually intended for interception of a certain portion of the light from a source and concentration of this light on a given area in such a manner that the image of this area is satisfactorily illuminated on a screen. The adequate description of a condenser includes: its equivalent focal length, the f/ number of the aperture ratio of the system with which the given

area is to be imaged, the distance of this area from the front vertex of the condenser, the distance of the rear vertex of the condenser from the specified light source. The performance of a condenser should be specified in accordance with the test specified in 5.1.2.20.

3.7 MISCELLANEOUS FEATURES. In describing a lens a number of miscellaneous features are encountered which do not directly relate to any particular aspect of this standard. These are listed with definitive and explanatory data.

3.7.1 *Performance designation.* Lenses are occasionally designated by the performance they are designed to supply relative to correction of specific geometrical aberrations, the three designations generally employed being achromat, anastigmat, and apochromat. These terms are defined in a general manner as follows.

3.7.1.1 *Achromat.* An achromat is a lens in which the EFL and BF have their values the same for light of two designated wave lengths. Also, the other aberrations are sufficiently well corrected for the use intended.

3.7.1.2 *Anastigmat.* An anastigmat is a lens in which the astigmatic difference is zero for at least one zone in the image plane. In such a lens the other aberrations are sufficiently well corrected for the use intended.

3.7.1.3 *Apochromat.* An apochromat is a lens in which lateral and longitudinal chromatic aberrations are smaller than the secondary spectrum residual in ordinary glass achromats, and three wave lengths are brought to a common focus. The other aberrations are sufficiently well corrected for the use intended. In some cases wherein the color corrections are not carried to the ulti-

¹¹ Veiling glare replaces the terms "stray light," "flare," "contrast rendition," and "specific brilliance" which are considered obsolete.

mate degree, the lenses are sometimes called semi-apochromats.

3.7.2 Reflection reducing coatings. Reflection reducing coatings on glass to air surfaces of elements consist of thin films of transparent substances. These substances are so applied and their indices of refraction so chosen that they form permanent hard coatings which substantially reduce reflectance at the surfaces for the spectral region to be used.

3.7.3 Environmental range. The maximum range of temperature, pressure, humidity, vibration, and biological conditions under which a lens can operate and be stored constitute its environmental range. The range required depends upon the intended use. Except when specified, the metrical and performance values covered by this standard apply to normal room temperature and pressure conditions.

3.7.4 Optical glass. Optical glass is a glass which during manufacture is carefully controlled with respect to composition, melting, heat treatment, and other processing in order that its optical characteristics, such as indices of refraction, dispersion, transmittance, spectral transmittance, freedom from birefringence, atmospheric stability, etc., have the values required for the optical application for which it is to be used.

3.7.4.1 Refractive index. When a ray is refracted at the surface of separation between air and a medium, the ratio of the sine of the angle of incidence in the air to the sine of the angle of refraction in the medium is equal to the refractive index of the medium.

3.7.4.2 Dispersion. Dispersion is the difference in refractive index between the C and F lines of hydrogen (in the absence of more specific requirements).

3.7.4.2.1 Dispersive power. Dispersive

power is the ratio of the dispersion from C and F to the refractive index of Sodium $n_D - 1$.

3.7.4.2.2 Abbe v number. The Abbe v number is the reciprocal of the dispersive power and is equal to $(n_D - 1)/(n_F - n_C)$.

3.7.4.3 Double refraction. When a light ray is transmitted through an anisotropic material, it is in general resolved into two rays polarized in perpendicular directions. This phenomenon is called "double refraction." It also occurs in a homogeneous material such as glass when elastically deformed or internally stressed. The maximum difference in index of refraction for rays polarized in different directions is called the "birefringence" of the material.

3.7.4.4 Chemical durability of glass. Chemical durability of glass is the resistance which the polished glass sample shows the corroding action of water, atmospheric agencies, and aqueous solutions of acids, bases, and salts.

3.7.5 Internal surfaces. Internal non-optical surfaces of lenses and lens mounts contribute to veiling glare by light reflected from them into the image space. Consequently, where needed so as not to contribute to veiling glare, lens barrels and, in some instances, lens cells should be knife-edge baffled; lens edges, mounts, barrels, cells, seats, and bores should be finished with a dull black light-absorbing material.

3.8 BEAUTY DEFECTS. Beauty defects are those imperfections of components and elements of an optical system which do not affect the optical characteristics. They are undesirable but may be accepted if they do not cause a significant degradation of image quality or environmental stability. The various imperfections classified as beauty defects are as follows.

3.8.1 *Material defects.*

3.8.1.1 *Bubbles.* Bubbles are air or gaseous inclusions entrapped within the glass.

3.8.1.1.1 *Seeds.* Seeds are very small bubbles.

3.8.1.1.2 *Air bells.* Air bells are irregularly shaped bubbles.

3.8.1.2 *Cracks.* Cracks are shallow separations or breaks in the glass.

3.8.1.3 *Feathers.* Feathers are powdered surfaces folded into the glass in the pressing process.

3.8.1.4 *Folds, or laps.* Folds, or laps, are areas in which the glass has been folded upon itself but not fused.

3.8.1.5 *Milkiness.* Milkiness is caused by cloudy or milky areas within the glass.

3.8.1.6 *Stones.* Stones are fragments of undissolved material in the glass.

3.8.1.7 *Strain.* Strain is tension within the glass caused by inadequate annealing or improper mounting. It is an area of index of refraction differing from the nominal.

3.8.1.8 *Striae.* Striae are streaks or veins in the glass with the index of refraction differing from that of the body of the glass.

3.8.1.8.1 *Reams.* Reams are fine bands of striae.

3.8.1.8.2 *Cords.* Cords are streaks of very heavy striae.

3.8.2 *Manufacturing defects.*

3.8.2.1 *Blisters.* Blisters are bubbles in a cement layer.

3.8.2.2 *Burns.* Burns are reddish stains generally ground on the central areas of elements. They are usually caused by the drying-up or glazing of a polisher.

3.8.2.3 *Cement starts.* Cement starts are spots where the components of a cemented lens have started to separate. They can be small irregular spots between the elements or run-ins at the edge, insufficient cement, or cement at the edge dissolved by a solvent.

3.8.2.3.1 *Run-ins.* Run-ins are cement separations at the edge of a cemented component.

3.8.2.4 *Chips.* Chips are areas from which glass has been broken away from the surface, edge, or bevel of an optical element.

3.8.2.5 *Cracks.* Cracks are breaks in the glass.

3.8.2.6 *Digs.* Digs are breaks of the polished surface of a round, oval, square, etc., shape including pits, holes, and surface broken bubbles.

3.8.2.6.1 *Dirt holes.* Dirt holes are digs filled with rouge.

3.8.2.7 *Dirt.* Dirt consists of dust, lint, or other foreign matter on the surface or entrapped in a cement layer.

3.8.2.8 *Grayness.* Grayness is represented by finely ground areas indicating incomplete or improper polishing.

3.8.2.9 *Mold marks.* Mold marks are marks on the surface produced by molding.

3.8.2.10 *Orange peel.* Orange peel is poorly polished surface, pock-marked with pits, having much the same surface appearance as the skin of an orange.

3.8.2.11 *Poor polish.* Poor polish pertains

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to polished surfaces containing minute pits of a gray or red color. They are gray grinding pits in the surface of the glass, or red grinding pits in which rouge has been so deeply embedded that it has to be removed by further polishing.

3.8.2.12 Scratches. Scratches are furrows or grooves in the surface of the glass caused by the removal of glass, usually made by coarse grit, fragments of glass, sharp tools, etc., rubbed over the surface.

3.8.2.13 Smears, scum, water spots, etc. Smears, scum, water spots, etc., are residue of evaporated or unevaporated moisture. They are usually removable by "normal" cleaning.

3.8.2.14 Stain. Stain is a discoloration of the glass surface, usually brown, blue, or green, caused by the deposit of foreign matter, or changes produced on the surface of the glass by chemical action of some substance with the glass.

4. GENERAL REQUIREMENTS

4.1 MARKINGS.

4.1.1 Lens markings. Lens markings, such as maximum aperture, focal length, field of view, and serial number shall be placed on the front of the lens cell or on the barrel if space limitations so require. The lens name and serial number shall be assigned by the manufacturer.

4.1.2 Cell marking. Lenses supplied in cells or constructed with removable cells shall have all cells permanently marked with at least the last three digits of the lens serial number.

4.1.3 Maximum aperture. All types of lenses, except types X and XI, shall be marked with their maximum aperture stated either as the relative aperture, aperture ratio or T-stop.

4.1.3.1 The symbol for relative aperture of a lens shall be $f/$ followed by the numerical value, for example $f/2.0$.¹²

4.1.3.2 The symbol for the T-stop of a lens shall be T followed by a space and then the numerical value, for example T 2.2.

4.1.3.3 f -number.¹² The effective diameter

of the maximum aperture of the lens shall be at least 95 percent of the quotient obtained by dividing the marked focal length by the f -number corresponding to the maximum marked aperture.

4.1.4 Iris diaphragm control marking.

4.1.4.1 Full stop.¹² The standard series of diaphragm markings, or stop openings, shall be 0.7, 1.0, 1.4, 2.0, 2.8, 4.0, 5.6, 8, 11, 16, 22, 32, 45, 64, 90, and 128.

4.1.4.2 Maximum aperture value.¹² The f -number corresponding to the maximum aperture, T-number, or aperture ratio value marked need not be selected from the above series but shall be followed by the above series of stop openings beginning with the next largest number whenever practical and progressing as far as required in the individual application; e.g., for an $f/1.9$ lens the diaphragm might be marked $f/1.9$, 2.8, 4.0, 5.6, 8, etc., if it was believed that to mark it $f/1.9$, 2.0, 2.8, 4.0, 5.6, etc., would confuse the marking at the $f/1.9$ end of the scale.

4.1.4.3 Fractional stop values. In addition to the numbered values, each stop may be divided into three subdivisions by dots or marks (not numbered), the dots being at "thirds of a stop," e.g., 0.7, 0.8, 0.9, 1.0, 1.12,

¹² American Standard Lens Aperture Markings, Z39.4.7-1940

1.26, 1.4, 1.5, 1.7, 2.0, 2.2, 2.5, 2.8, 3.2, 3.6, 4.0, 4.5, 5.0, 5.6(6), 6.3, 7.1, 8.0, 9.0, 10.0, 11.(3), 12.7, 14.2, 16, 18, 20, 22.(6), 25, 28, 32.

4.1.4.4 Tolerance of marking. For a lens marked in relative apertures, if the setting for a given indicated value is made by proceeding from a larger to a smaller opening (to insure constancy of direction for elimination of backlash), the marked value shall not be in error by more than one-third of a stop (plus or minus 12 percent of the diameter or plus or minus 25 percent of the area of the effective aperture). Under similar conditions, if the lens is graduated in T-stops, the errors shall not exceed one-tenth of a stop (plus or minus 7 percent of the central image illuminance).

4.1.5 Focal length.¹³

4.1.5.1 All lenses which are marked with the equivalent focal length shall indicate this value by the letters EFL followed by the numerical value either in the English or the Metric system as required by the individual application.

4.1.5.2 The accuracy of the marked focal length shall be as required by the individual application.

4.1.5.3 Accuracy of focusing scales. Focusing scales, when required, shall be accurately marked to indicate the correct focus position of the corresponding lens to an accuracy of $\pm ds$, where $ds = CN$. N is defined by equation (2) in 3.2.2, and C is a constant which may be related to the circle of confusion or the permissible resolving power. The value of C is determined by the individual application.

5. DETAIL REQUIREMENTS

5.1 METHODS OF TEST AND MEASUREMENT. This section deals with methods of testing and measuring properties related to photographic lenses. In many cases particular details are not provided but will be determined by the individual application. Whenever alternate methods of testing or measuring are given, the method shall be employed which is most convenient and which best agrees with the intended use of the lens. When this standard is used in reference to the procurement of photographic lenses, only those tests specifically designated shall be used in the examination of the prod-

uct. The procurement shall also clearly state which tests apply to 100 percent inspection and which tests are to be used only for the examination of samples.

5.1.1 Test apparatus. The criteria to be used in judging the suitability of test apparatus are as follows:

5.1.1.1 Collimator. A collimator is a device by which a test object (pinhole, resolution chart, etc.) is made to appear at an infinite distance from the observer. It commonly consists of a well-corrected telescope objective or catadioptric system with the test object mounted accurately in the focal plane. The collimator aperture relative to the lens shall be such that the entrance pupil of the lens is filled with light of uniform illuminance from every part of the collimator field.

5.1.1.2 Optical bench and nodal slide. The

¹³ American-British-Canadian Air Standardization Agreement. Focal Lengths of Lenses for Air Reconnaissance and Mapping Cameras. ABC AIR STD 52/4. 15 March 1956. For aerial reconnaissance cameras, the following focal lengths are standardized: 1 1/2 inches, 2 1/4 inches, 3 inches, 4 1/2 inches, 6 inches, 9 inches, 12 inches, 18 inches, 24 inches, 36 inches, and 48 inches, etc., and the focal lengths are to be marked in inches. For mapping cameras, the following nominal focal lengths are standardized: 6 inches, 12 inches, 18 inches, 24 inches, and the nominal focal lengths are to be marked in inches. However, there would be no objection to some deviations from the focal lengths below 6 inches, should this prove to meet special applications.

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microscope objective on the test bench shall have a numerical aperture " $n \sin \alpha$ " greater than " $n \sin \alpha$ " (see equation (2) in 3.2.2) of the lens being tested. When examining the edge of the field of a lens, the numerical aperture of the microscope objective shall be sufficiently large to permit it to intercept both principal and edge rays. Alternately, the microscope may be mounted on a vertical pivot permitting this to be accomplished. In this case, the axis of the pivot must pass through the object point of the microscope. For reference, table I shows the numerical apertures and their corresponding f-numbers.

TABLE I

Numerical aperture	f-number
0.0175	f/28.7
0.0349	f/14.3
0.0523	f/9.55
0.0698	f/7.15
0.0872	f/5.74
0.1737	f/2.88
0.2588	f/1.93
0.3420	f/1.46
0.4226	f/1.18
0.5000	f/1.00
0.5736	f/0.872
0.6428	f/0.778
0.7071	f/0.707
0.7660	f/0.653
0.8192	f/0.610
0.8660	f/0.577
0.9063	f/0.552
0.9397	f/0.532
0.9659	f/0.518
0.9848	f/0.508
0.9962	f/0.502
1.0000	f/0.500

5.1.1.3 *Infinity*. When testing a lens at "infinite" focus by means of a target at a finite distance, the distance shall be considered approximately infinite when it is greater than D measured in feet

$$D = 400 fd \quad (12)$$

where d is the diameter of the effective aperture in inches, and f is the EFL in inches

of the lens being tested. The distance D is not to be used in determining the EFL directly, unless a suitable correction is made for the plane of best infinite focus. However, a distance D may be used for focusing and checking resolution of fixed focus cameras and cones at infinity. For checking infinity focus resolution only, designated values less than that of D in formula (12) may be used unless, as in some cases, there is a noticeable loss in resolving power when a lens intended for use at infinity is tested at finite distance.

5.1.1.4 *White light*. White light will usually be used in conducting all tests. For most photographic tests, the spectral composition of "white light" is not critical and any source of light, ordinarily considered free from color, may be used. For purposes of this standard, white light is defined as black body radiation of 2750°K to 6000°K. When required, the white light may be filtered to a particular color. (The detailed specification shall state whether or not the filters supplied with the lens shall be used when conducting resolving power tests.)

5.1.1.4.1 *Flash discharge lamps*. Flash discharge lamps will be permitted for making test exposures provided care is taken to insure controlled charging of the lamp condenser so that successive exposures are approximately equal during the photographic testing process.

5.1.1.5 *Photographic plates and film*. The photographic sensitized material and the processing used in the testing of all types of lenses shall be the kinds most commonly used with the type of lens being tested. (See 5.1.2 12.1.)

5.1.1.6 *Test conditions*. Unless particularly required by the intended uses, all tests and measurements shall be conducted under normal room conditions.

5.1.1.7 *Resolving power target*. The re-

solving power target used on all tests shall be as follows: The target shall consist of a series of patterns decreasing in size as the $\sqrt{2}$, $\sqrt[3]{2}$, $\sqrt[4]{2}$, with a range sufficient to cover the requirements of the lens-film combination under test. The standard target element shall consist of two patterns (two sets of lines) at right angles to each other. Each pattern shall consist of three lines separated by spaces of equal width. Each line shall be five times as long as it is wide. (See Figure 7.) For types I and II lenses, targets with light lines on a dark background are preferred; for types IV, VI, VII, XII, XII lenses, targets with dark lines on a light background are preferred. The target contrast (the difference in photographic density between the lines and spaces) shall be either high, medium, or low contrast, as specified.

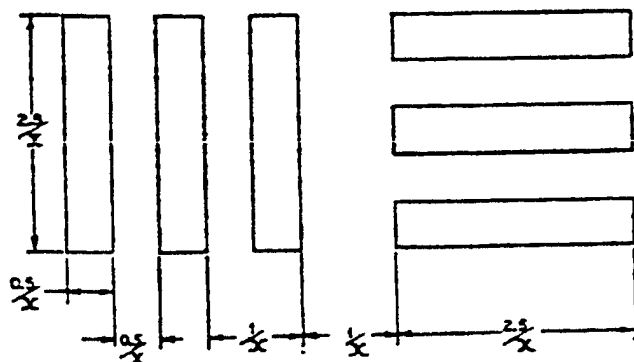


FIGURE 7. Standard Resolving Power Test Target Element. The patterns of lines are parallel lines $2.5 \times$ millimeters long and $0.5 \times$ millimeters wide with space $0.5 \times$ millimeters wide between the parallel lines, where x equals the numbers of lines per millimeter.

5.1.1.7.1 High contrast target. A high contrast target is one in which the density difference between the light and dark areas is greater than 2.00.

5.1.1.7.2 Medium contrast target. A medium contrast target is one in which the density difference between the light and dark areas is equal to 0.80 ± 0.05 .

5.1.1.7.3 Low contrast target. A low contrast target is one in which the density dif-

ference between the light and dark areas is equal to 0.20 ± 0.05 .

5.1.2 Test methods.

5.1.2.1 Plane of best definition. The plane of best definition is usually determined by making a series of evaluations at a sufficient number of focal settings. The distance between focal settings in hundredths of millimeters shall be at least

$$\frac{\text{f-number of lens}}{\text{no. of lines/mm. expected}}$$

The detailed specification shall state the method used in determining the plane of best definition.

5.1.2.2 Equivalent focal length.

5.1.2.2.1 Method 1 — Photographic method.¹⁴ The EFL shall be measured by placing a photographic plate in the focal plane of the image space. Unless otherwise specified, the focal plane is defined as the place of best photographic imagery for an infinity distant axial point; the focal plane may also be specified as the plane of best definition. A collimator and reticle may be conveniently used to provide an infinitely distant object point. Exposures are made with the beam of light from the collimator directed along the optical axis of the lens and a series of angles β_1, β_2 , etc. On the resultant negative, measurements shall be made of the distances γ_1, γ_2 , etc., from the axial images to the images corresponding to the angles β_1, β_2 ,

$$\text{etc., and the quotient } \frac{\gamma_1}{\tan \beta_1}, \frac{\gamma_2}{\tan \beta_2}$$

etc., formed. The limiting value of this quotient as β approaches zero is the EFL. In a photographic objective free from distortion, the quotient is invariant with respect to the

¹⁴ American Standard Methods for Designating and Measuring Focal Lengths and Focal Distances of Photographic Lenses. Z39.4.21-1948.

value of β . For many photographic purposes the distortion is negligible for points distant from the center of the useful field not more than one-fifth of its radius, and consequently, it will very often be possible to obtain a satisfactorily accurate value of the EFL by a single determination of β and γ for a point lying near the axis.

5.1.2.2.1 Method 1A — Combination method. The EFL also may be determined by adding the photographic BF to the distance from the rear vertex to the emergent nodal point. The latter distance may be determined by Method 2.

5.1.2.2.2 Method 2 — Nodal slide method. The lens to be tested shall be mounted on a nodal slide to rotate about the vertical axis through its second nodal point. The distance from this nodal point to the position of best axial focus for an infinitely distant object point shall be measured. This is also known as the second principal focus. (An important factor or uncertainty in using this method is the difference between the position of best focus as judged visually on the optical bench and the best focus as determined photographically by method 1). When using this method, the criterion for determining the best axial focus should be specified. The criterion used is dependent on the type of test object or target used and may be specified in terms of either the haze position or the position of greatest concentration (see 3.6.9.1.1 and 3.6.9.1.2) or in terms of the color in and around the image.

5.1.2.3 Calibrated focal length. When determining the calibrated focal length, the plane of best average definition shall be chosen as the focal plane. To compute the calibrated focal length, let γ_1 , γ_2 , etc, represent the distances in the focal plane from the axial point to the images of infinitely distant object points lying in the directions making angles β_1 , β_2 , etc., with the optical axis of the objective. If f is the equivalent

focal length in the absence of distortion, then

$$\begin{aligned}\gamma_1 &= f \tan \beta_1 \\ \gamma_2 &= f \tan \beta_2\end{aligned}\quad (13)$$

$$\text{and } \gamma_s = f \tan \beta_s \quad (14)$$

In the presence of distortion

$$\begin{aligned}\gamma_1 &= f \tan \beta_1 + \Delta \cdot \gamma_1 \\ \gamma_2 &= f \tan \beta_2 + \Delta \cdot \gamma_2\end{aligned}\quad (15)$$

$$\text{and } \gamma_s = f \tan \beta_s + \Delta \gamma_s \quad (16)$$

The added terms are the values of the linear distortion for values β_1 , β_2 , etc., respectively. The values of γ and β are measured directly. It is evident that the individual values of the distortion defined by the above group of equations can be changed by changing the value of f . If f is the equivalent focal length, in many instances values of the distortion in the neighborhood of the axial image point will be small, and near the edge of the field the values will be large and predominantly negative or positive. Infinitely distant targets may be provided by a group of collimators or by one collimator which can be successively placed in the required angular positions. Exposures shall be made and the γ corresponding to each angular distance from the optical axis shall be determined.

5.1.2.4 Back focal distance.¹⁵ To determine the BF, the focal plane in the image space shall be determined by a visual or photographic method. The measured distance from this focal plane to the vertex of the back surface of the lens shall be the required BF.

5.1.2.5 Flange focal distance.¹⁵ To determine the FD, the focal plane in the image space shall be determined by a visual or photographic method. The measurement shall be made from the plane of the locating surface or the flange to the focal plane.

5.1.2.6 Front focal distance.¹⁵ To determine the FF, the focal plane in the object space shall be determined by a visual or

¹⁵ See footnote 14, page 50.

photographic method. The measured distance from this focal plane to the vertex of the front surface of the lens shall be required FF.

5.1.2.7 Front vertex back focal distance. To determine the FVD, the focal plane in the image shall be determined by a visual or photographic method. The measured distance from the vertex of the front surface of the lens to the focal plane shall be the required FVD.

5.1.2.8 Aperture ratio. For the special case in which the object is at infinite distance (magnification = 0), N , the first member of the ratio equation (2) in 3.2.2, may be determined as the quotient obtained when the EFL is divided by the diameter of the effective aperture.

5.1.2.8.1 For the general case in which the magnification may have any value, a pinhole should be mounted at the axial point of the desired image plane, and the angle of the cone of light emerging through the pinhole from the lens should be determined by measuring the diameter of a right section of the cone at a suitable distance beyond the pinhole. The angle α can be calculated from the measurements and substituted in equation (2). If n is the index of refraction of the medium in which the angle α is measured ($n = 1$ for air, used in the great majority of cases), the second member of the

aperture ratio is
$$\frac{2n \sin \alpha}{1}$$

When measuring the aperture ratio by the method of this paragraph, the angular subtense of the object point at the first nodal point of the photographic objective must be small as compared with the value of the angle α between the optical axis of the objective and the extreme ray proceeding to the image point.

5.1.2.9 Effective aperture.

5.1.2.9.1 Method 3 — Microscope method.¹⁶ A traveling compound microscope is required with means for translating the microscope in a direction at right angles to its optical axis through a measured distance not less than the diameter of the maximum effective aperture to be measured. The microscope must be of low power (10X to 20X) provided with a reticle and with a working distance sufficiently long to permit the microscope to be focused on the limiting opening of the photographic objective through the front member. The photographic objective, of which the effective aperture is to be measured, shall be mounted in a convenient position to permit the traveling microscope to be directed parallel to the optical axis of the objective and focused upon the edge of the opening having the smallest apparent diameter. (The photographic objective is not to be disassembled.) This edge shall be viewed through the lens elements which are normally traversed by image-forming light before passing through the limiting opening. A microscope having a long working distance is required to avoid mechanical interference when looking through the lens elements. A microscope shall then be traversed and measurements made to determine the apparent diameter of this opening which shall be the effective aperture. In place of a traveling microscope, a suitable contour projector may be employed to measure the effective aperture. If the lens has a non-circular aperture, the measured diameter must be suitably corrected.

5.1.2.9.2 Method 4 — Point source method.¹⁷ When it is not practicable to use a microscope of sufficient working distance to permit the limiting opening to be observed through the lens elements, a source of light, as small as practicable and emitting a cone sufficiently large to fill the lens, may be

¹⁶ American Standard Methods of Designating and Measuring Apertures and Related Quantities Pertaining to Photographic Lenses, Z39.4.20-1943.

¹⁷ American Standard Aperture Calibration of Motion Picture Lenses, PH27.90 — 1953.

placed at the second principal focus and directed toward the objective; the diameter of the emergent beam should be measured as near the front of the objective as is practicable. This method is subject to a systematic error, the value obtained always being too large, because of the finite size of the source.

5.1.2.10 *T-number and transmittance.* The equipment specified in methods 5 and 6 for determining T-stops and transmittance of a lens represents workable apparatus. However, modifications are permitted provided that the basic requirements of the method and the specified accuracy are met. (See 3.2.6 and 4.1.4.4.)

5.1.2.10.1 *Method 5 — Extended source method.*¹⁸ This method of lens calibration is based on filling the lens with light from an extended uniform source of adequate size and placing in the plane of best definition of the lens a metal plate with a hole, the diameter of which shall not exceed 3 millimeters (or 1.5 millimeters for 8-millimeter film), at its center. The light flux passing through the hole shall be measured by a photocell arrangement. This flux shall then be compared with the flux passing through a hole of the same dimensions from an open circular aperture of such a size and at such a distance from the plate that it subtends the desired angle α so that $\sin \alpha = \frac{1}{2} T$, where T is the T-number to be measured. The greatest care is necessary to insure that the extended source is uniform. In practice, the photocell reading for each whole T-number is first determined for a series of open apertures at a fixed distance from the plate. The lens is then substituted for the open aperture with the 3-millimeter hole accurately in its focal plane and the iris of the lens closed down until the photocell meter reading produced by the lens is equal to each of the successive open hole

readings. The full T-stop positions are then marked on the diaphragm ring of the lens. The intermediate thirds of stops may be found with sufficient accuracy by inserting a neutral density filter of 0.1 and 0.2 behind each open aperture in turn and noting the corresponding photocell readings or by dividing the travel of the diaphragm control into three equal parts. The extended source should be uniformly bright over its useful area to within ± 3 percent. (This could be tested with a suitable telephotometer, or a small hole in an opaque screen could be moved around in front of the source and any consequent variations in photocell reading noted.) The source may be a sheet of ground glass covering a hole in a whitelined box containing several lamps mounted around the hole and shielded so that no direct light from the lamps falls on the ground glass itself. The photocell receiver may be of the phototube type with a simple d-c amplifier. Care must be taken to insure that phototube sensitivity does not change between marking readings on the open aperture and on the lens itself. To guard against this, some turret arrangement is desirable, with the lens on one side and the open aperture on the other, so that the two may be interchanged and compared quickly with each other by turning the turret. Transmittance of a lens shall be measured at the maximum relative aperture in a direction parallel to the optical axis of the lens. Transmittance is equal to C/R where C is the calibrated photocell reading with the lens in place, and R is a similar reading when a clear circular aperture is in place, subtending an angle α at the hole in the front of the photocell so that $\sin \alpha = \frac{1}{2} N$, where N is the second term in the aperture ratio of the lens to be tested. (See 3.2.2.) The value of N must be the true value, which may differ from that indicated on the barrel.

5.1.2.10.2 *Method 6 — Collimator method.*¹⁹ In this method, light from a small

¹⁸ See footnote 17, page 66.

¹⁹ See footnote 17, page 66.

source (a 5-millimeter hole covered with opal glass and strongly illuminated from behind) shall be collimated by a simple lens, or an achromat if preferred, of a focal length at least three times the EFL of the lens being tested and of sufficient aperture to fill the lens being calibrated. This gives a collimated beam which will be focused by the test lens to form a small circle of light in its focal plane. This circle of light will be less than the prescribed limit of 3 millimeters diameter. Uniformity of the collimated beam can be checked by moving a small hole in an opaque screen across the beam, and noting any variations in the photocell reading. For the comparison unit, an open aperture shall be used, of diameter equal to the focal length of the lens divided by the desired T-number. This aperture shall first be mounted in front of an integrating sphere of adequate size with the usual photocell detector and the light from the collimator allowed to enter the aperture. The aperture plate shall then be replaced by the lens, the iris diaphragm closed down to give the same photocell reading, and the T-number engraved on the iris ring. The intermediate thirds of stops can be found by using 0.1 or 0.2 density filters, or by dividing the travel of the diaphragm control into three equal parts. To guard against "drift" or line-voltage variations which might occur between readings of the comparison aperture and the lens, it is convenient to leave the known standard aperture in place in front of the sphere, and to insert the lens into the beam in such a position that the small image of the source falls wholly within the standard aperture. The meter reading should then remain the same with the lens in or out of the beam. A second plate with a 3-millimeter aperture should be placed over the comparison aperture while the lens is in place to stop any stray light which may be reflected from the interior of the lens. It should be noted particularly that if this method is used, the focal length of the lens must be

measured separately and a suitable set of open apertures constructed for use with it. However, by suitable devices, one single set of fixed apertures may be used for all lenses. Transmittance of a lens shall be measured at the maximum relative aperture in a direction parallel to the optical axis of the lens. Transmittance is equal to C/R where C is the calibrated photocell reading with the lens in place, and R is a similar reading when a clear diaphragm (equal to the lens effective aperture) is in place.

5.1.2.11 *Relative illumination.*

5.1.2.11.1 Method 7 — Extended source method. This method of measuring relative illumination makes use of the same apparatus and techniques specified in method 5. With the lens to be measured set up in the apparatus, the photocell shall be displaced laterally to the position corresponding to the required angular positions, and the corresponding percentage of axial illuminance for each position is found from a calibration curve of the photocell meter.

5.1.2.11.2 Method 8 — Collimator method. This method of measuring relative illumination makes use of the same apparatus and techniques specified in method 6. With the lens to be measured set up in the apparatus, the lens shall be rotated through the desired field angles β and the photocell readings compared with the readings for the lens on axis. The percentage of light flux transmitted can then be read off a calibration curve for the photocell system and converted to desired percentage illuminance by dividing by $\cos^3 \beta$.

5.1.2.11.3 Method 9 — Densitometric method. This method of measuring relative illumination makes use of the same apparatus and techniques as specified in methods 5 and 6, except that a photographic plate is substituted for the photocell when the extended source is used, and for the integrating sphere

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when a collimator is used. In the latter case, the image produced by the lens should be in sharp focus on the emulsion plane. The exposures are made on the axis and at the required angular positions off axis. The exposure times shall be the same at all the positions. The densities of the exposed and developed images shall be measured and the relative illuminance determined using the sensitometric curve of the emulsion, obtained by exposing a calibrated step-wedge.

5.1.2.11.4 Method 10 — Indirect computation method. The indirect computation of illuminance distribution from dimensions of the lens are outlined in this section. The method in this case is for a lens while in the design stages, or in determining the illuminance distribution of an actual lens when no convenient photometric equipment is available.

5.1.2.11.4.1 Distortionless lens with object at infinity. The case where the object is at infinity is applicable to most photographic objectives encountered in aerial and ground photography. The field angle of such a lens is always expressed by the obliquity angle ϕ , in the object space. The desired relative illumination is given by:

$$R = \frac{E_{\phi}}{E_0} = \frac{S_{\phi}}{S_0} \cos^4 \phi \quad (17)$$

where E is the illuminance at the point in the image which corresponds to the obliquity angle ϕ in the object space, and E_0 is the illuminance at the center of the field. S_{ϕ} and S_0 are, respectively, the beam section areas of the oblique and axial beams at the chosen reference plane in the object space. The area S_{ϕ} will in general be smaller than S_0 due to vignetting, but in some unusual lenses, S_{ϕ} may be somewhat greater than S_0 .

5.1.2.11.4.2 Distortionless lens with finite object distance. The relative illumination R can be computed either in the object space

or in the image space depending on which is more convenient. The illuminance at angle ϕ is given by the integral:

$$E_{\phi} = K / \cos^4 \phi dS = K' / \cos^4 \phi' dS' \quad (18)$$

where K and K' are constants independent of obliquity. The integrals are to be taken over the respective beam sections. The integrals are necessary because ϕ and ϕ' vary from point to point over the beam sections. If the aperture is small, the integral becomes unnecessary and then:

$$E_{\phi} = K S_{\phi} \cos^4 \phi = K' S'_{\phi} \cos^4 \phi' \quad (19)$$

The relative illumination is then found by evaluating E_{ϕ} and E_0 for an oblique and axial beam and taking the ratio $R = E_{\phi}/E_0$.

5.1.2.11.4.3 Distorting lens with object at infinity. This differs from the previous case because the distortion will have a considerable effect on the distribution of illuminance expressed as a function of the entering obliquity angle ϕ . In this case the relative illumination becomes:

$$R = \frac{E_{\phi}}{E_0} = \frac{S_{\phi}}{S_0} \frac{f^2 \sin \phi \cos \phi}{h' (dh'/d\phi)} \quad (20)$$

S_{ϕ} and S_0 are the areas of the beam sections for the oblique and axial beams at the chosen reference plane in the object space; ϕ is the obliquity angle in the object space, f is the focal length of the lens and h' is the image height. By measurements or computations on the lens, a relation can be established connecting h' with ϕ , from which the value of the derivative $dh'/d\phi$ can be found at any desired point in the field. For a distortionless lens, $h' = f \tan \phi$; in that special case equation (20) simplifies to equation (17).

5.1.2.11.4.4 Distorting lens with finite object distance. The image space equations (18) or (19) hold independent of the distortion of

the lens. If it is desired to use the data of the object space, equation (18) becomes:

$$E_{\phi} = K \frac{h}{h' (dh')} \int \cos^4 \phi \, dS \quad (21)$$

(dh)

where K is a constant different from that used in equation (18), h is the object height, and h' the height of the image of that object. The derivative dh'/dh must be found by determining an algebraic relationship between h and h'. If the aperture is sufficiently small, ϕ will not vary greatly over the beam section and the equation may be reduced to the approximate form.

$$E_{\phi} = K \frac{h}{h' (dh')} S_{\phi} \cos^4 \phi \quad (22)$$

(dh)

5.1.2.11.4.5 Monocentric lens. In the case of a lens having a common center of curvature to all the surfaces and a concentric image surface, the relative illumination contains only one cosine, namely:

$$R = \frac{E_{\phi}}{E_0} = \frac{S_{\phi}}{S_0} \cos^4 \phi \quad (23)$$

5.1.2.12 Resolving power. When specifying or measuring resolving power, care should be taken to consider the following pertinent factors: methods of tests, contrast of target used, kind of and processing of photo-sensitive emulsion, whether filter is to be used, and magnification at which resolving power target images are read. For reading resolution, a magnification of the lowest power which permits convenient viewing will yield the highest resolution readings. (The rule based on Selwyn's experiments²⁰ that

the numerical value of the magnification should equal the number of lines per millimeter expected to be resolved can be considered a rule of thumb.)

5.1.2.12.1 Photographic resolving power.

When conducting photographic resolving power tests by methods 11 and 12, the photo-sensitive material and processing should be in accordance with table II.

5.1.2.12.1.1 Method 11 — Collimator method.²¹ For lenses primarily intended for use on distant objects, such as types I, II, III, and V, this method should be used. The resolving power target is placed at the principal focus of a collimator and illuminated with white light. A filter of a specified color may be used and it shall be placed between the light source and the target. It is recommended that, in order to eliminate vibration effects, a flash discharge lamp be used as the light source and that the light from it be filtered if necessary to approximate white light. (See 5.1.1.4.) Exposure can be controlled by means of neutral density filters between the light source and the target. The lens to be tested shall be placed in the collimated beam from the target and a test plate or film made in a series of focal settings as described in 5.1.2.1. Unless otherwise specified, the lens shall be set at the specified maximum relative aperture. With the test plate perpendicular to the optical axis of the lens, exposure shall be made of the test target at the specified angular distance from the axis out to and including the multiple of the specified angle falling nearest the corner of the plate inside the picture format. The specified angle should be multiples of 1¼ degrees and should be spaced to provide 5 increments or more in the semi-field of the lens. The exposure time shall be the same for all angular settings and shall be the

²⁰ E. W. H. Selwyn, National Bureau of Standards CS24, 219, 1954 and *Photographic Journal* 90B, 46, 1948

²¹ In method 11, if the resolving power is measured by reticulating from (or lines per millimeter of the target, EFL of the collimator, and EFL of the test lens, the value should be corrected by multiplying radial lines by the cosine of the field angle and tangential lines by the root of the field angle.

TABLE II

Lens type	Photosensitive material	ASA Exposure index	Development (gamma)
I (70-mm. format & smaller)	Panchromatic aerial	10	2.0 ± 0.10
(5-inch format & larger)	Panchromatic aerial	80	1.5 ± 0.10
II (70-mm. format & smaller)	Panchromatic aerial	10	2.0 ± 0.10
5-inch format & larger)	Panchromatic aerial	80	1.5 ± 0.10
III	Panchromatic aerial	50	0.8 ± 0.10
IV	Panchromatic microfilm	...	Maximum contrast
V	Panchromatic (motion picture)	50-80	0.6 ± 0.10
IX	Panchromatic (portrait)	100	0.6 ± 0.10
XII	Panchromatic microfilm	...	Maximum contrast
XIII	Panchromatic microfilm	...	Maximum contrast
XIV	Blue sensitive recording	...	1.5 ± 0.10

exposure time which gives the highest resolving power at the angular setting nearest the angle equal to one-half the half angle of view. The different angular settings may be obtained by moving the lens and test plate about an axis near the entrance pupil or by moving the collimators, or by means of a series of collimators placed in the correct angular positions. The lens may be tested with or without the filter provided with it, as required.

5.1.2.12.1 Method 12 — Target range method. For lenses primarily intended for use at finite distances, such as types IV, XII, and XIII, this method should be used. Also, it may be used, when specified, for testing other types of lenses. Properly illuminated high contrast resolving power targets shall be placed in the object space in a plane perpendicular to the optical axis of the lens to be tested and spaced at the required angular distances. The distance from the lens to the plane of the targets shall be designated. When this method is used for testing lenses at infinity focus, either formula (12) in 5.1.1.3 may be used to determine the proper distance, or some designated distance may be used. The test plate shall be adjusted per-

pendicular to the optical axis of the lens and exposed for maximum resolution at the target nearest the angle equal to one-half the half angle of view of the lens being tested and shall be moved in a series of focal settings as described in 5.1.2.1. The sensitized material, processing, etc., shall be in accordance with table II.

5.1.2.12.2 Method 13 — Visual resolving power. When visual resolving power measurements are required (such as type X lenses), they will be made exactly like the photographic resolving power tests, except that the aerial image, when it is real and easily available, will be observed visually under magnification. Method 11 or 12 in 5.1.2.12.1 will be used as specified, depending on the use of the lens. When the image formed by a viewfinder (type X lens) is a virtual image, a telescope stopped down to 5 millimeters and placed at the eye position will be used to observe the image. In this case the resolution shall be determined in terms of a specified test chart at a specified distance. In all cases where the image is formed on a ground glass, the ground glass shall be removed to observe the aerial image, and the image shall be observed on a plane.

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5.1.2.12.3 Method 14 — Projected photographic resolving power. This test is intended to be used primarily for enlarging lenses (type VI). A target plate of the required size containing resolving power targets (light lines on a dark background) and of the required range, and located as shown in Figure 8, with one set of the lines in tangential and the other set in radial direction, shall be placed in the object plane (film plane) of the lens to be tested. The targets shall be of high contrast. The target plate shall be evenly illuminated by light from a condensing source. If required, the light shall be filtered to the color required by placing a filter between the light source and the target plate. With the optical axis of the lens perpendicular to the target plate, the lens shall be focused at the designated magnification and aperture, and an exposure made on the designated photosensitive material. The photosensitive material shall be held flat in a plane perpendicular to the optical axis of the lens. The correct exposure shall be that which gives the maximum resolution at position B of Figure 8. The test plate is processed in the required manner. The resolving power shall be read by observing the dry test plate under suitable magnification. The figures referred to in measuring resolving power by this method are the lines per millimeter on the target plate. It is recommended that enlarging lenses be tested at a magnification of 1:2 using medium contrast glossy chlorobromide paper processed 1½ minutes in D72 developer, diluted 1:2 at 68° F.

5.1.2.12.4 Method 15 — Projected visual resolving power.²² This test is intended to be used primarily for projection lenses (type VII). A test object of the required size containing high contrast resolving power targets (dark lines on light background) of the required range and placed as shown in Figure

²² American Standard Method for Determining Resolving Power of Lenses for Projectors for 35-mm. Slide Film and 2 x 2-inch Slides, FED .16-1047 (Revised 1962).

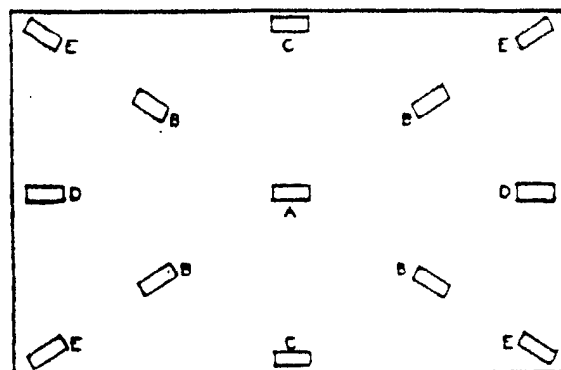


FIGURE 8. Projected Resolving Power Test Plate

under test upon a matte, white, grainless screen. This screen shall be located at such a distance from the projector that unless otherwise specified the long dimension of the projected image will be at least 40 inches in order that the observer will have no difficulty in distinguishing the number of lines resolved. The resolving power of the lens at any point in the field is the largest number of lines per millimeter in the test object that an observer, close to the screen, sees definitely resolved (easily counted) in both radial and tangential directions in the projected image. Care shall be taken to insure that the screen is perpendicular to the optical axis of the projection lens, and that the lens is focused so that the image at the center of the test plate has maximum contrast. The projector used in this test may be a regular production model or a special test projector. The glass test object shall be flat and held concentric with and normal to the optical axis of the projection lens. The cone of light from the projection lamp through a condensing system shall completely fill the entrance pupil of the projection lens. The test object shall be uniformly illuminated.

5.1.2.13 Astigmatism and curvature of field.

5.1.2.13.1 Method 16 — Resolving power target method. By means of any of the methods for measuring resolving power specified in methods 11 through 15, resolving power

shall be determined for different positions of the test plate in the image space. The test plate or plates are exposed in small steps, at different distances along the optical axis of the lens. The length of each step depends upon the corrections, focal length, and aperture of the lens being tested. A sufficiently large number of steps shall be taken to insure at least three steps on each side of the best focus position for both radial and tangential lines at any angular position. Upon reading the targets, the position of best focus shall be determined (for radial and tangential lines separately) at which the resolution is a maximum at each angular setting. These focus positions are plotted against angular settings, and two curves representing the two image surfaces are obtained. The curve representing curvature of field is a median drawn between the two curves representing the image surfaces. (See 3.6.3.) The astigmatic difference is obtained by taking the difference in the focal setting at a specific angle for the two image surfaces.

5.1.2.13.2 Method 17 — Nodal slide method. This method may be used in lieu of method 16. In this method the lens to be tested shall be set up in front of a suitable collimator equipped with a target containing vertical and horizontal lines and centered so that the optical axis is parallel to the collimator axis and coincident with the axis of the observing microscope. The lens shall be moved along the microscope axis until the axis of rotation of the nodal slide intersects the rear node. The microscope shall be focused on the axial image and the position of the microscope noted. The lens shall then be rotated about the axis through the rear node and perpendicular to the optical axis of the lens. At multiples of angular positions of $1\frac{1}{4}$ degrees out to the edge of the field, the microscope shall be separately focused on the radial and tangential lines. The focal change from the axis position shall be noted at the angular field positions for the radial and tangential lines. To obtain curves such as

specified in method 16, the factor $f(1 - \cos \beta) / \cos \beta$ is subtracted from the microscope settings, and this difference is multiplied by the $\cos \beta$. If a flat field bar is used at the microscope it is not necessary to subtract the factor $f(1 - \cos \beta) / \cos \beta$. When curves are obtained, the procedure for determining the curvature of field is the same as that in method 16.

5.1.2.14 Color correction. When the image quality is found satisfactory on the basis of other applicable tests, the color correction can also be considered as satisfactory. Direct measurements of color corrections may be needed when some special color requirements are to be met. These measurements may be specified in terms of minimum resolving power or limits on individual color corrections.

5.1.2.14.1 Longitudinal chromatic aberration.

5.1.2.14.1.1 Method 18 — Photographic method. Photographic resolving power measurements shall be made as specified in method 11 or 12, utilizing light of the colors designated, repeating the test for each color. The light used may be supplied by a monochromator or it may be filtered white light, as specified. The focus positions at which the maximum resolving power (AWAR unless otherwise specified) is obtained shall be determined for each color. The longitudinal color aberration for a particular color is the difference in focal setting for this color and white light, or for this color and a specified color. When the focal setting for the first color is greater than the focal setting for the reference color or white light, the longitudinal chromatic aberration is said to be positive. Generally, the reference color should be towards the red end of the spectral range under consideration.

5.1.2.14.1.2 Method 19 — Nodal slide method. When specified, a nodal slide optical

bench may be used instead of a test camera as in method 18.

5.1.2.14.2 *Lateral chromatic aberration.*

5.1.2.14.2.1 *Method 20 — Photographic method.* Photographic measurements shall be made in the plane of best average definition for white light or a specified reference color. The image sizes γ'_1 , γ'_2 , etc. are measured, as specified in method 1, for different colors. The lateral color aberration at a particular angle is the difference between γ' for the particular color and γ' for the white light or the specified reference color.

5.1.2.14.2.2 *Method 21 — Nodal slide method.* When specified, a nodal slide optical bench may be used instead of a test camera in method 20. Lateral chromatic aberration shall be measured by moving the optical bench microscope along a scale perpendicular to the axis of the optical bench, first sighting the microscope on the image formed by using white light, or light of the second specified color. When setting the microscope for measurements at each angle β , the microscope shall be displaced along its horizontal axis by the distance $f(1 - \cos \beta) / \cos \beta$ away from the lens. This refocusing is not necessary if a flat field bar is used. This setting of the microscope is maintained at each angle for all the colors. The distance through which the microscope is moved laterally, divided by the cosine of the angle at which the measurement is made, is the lateral chromatic aberration.

5.1.2.15 *Magnification.*

5.1.2.15.1 *Paraxial magnification.*

5.1.2.15.1.1 *Method 22 — Photographic method.* The PM shall be measured by placing a photographic plate in the image plane conjugate with the object plane at the spe-

cified finite distance from the lens. Within the intended field of coverage in the object plane, a series of reticles is placed at accurately determined distances γ_1 , γ_2 , etc., from a reticle at the axial object point. (The exact location of this point is not needed, and any point in the vicinity of the intersection of the lens axis with the object plane may serve as reference for measuring distances γ .) A photograph is taken of the array of the reticles. On the resulting negative, measurements shall be made of the corresponding distances γ'_1 , γ'_2 , etc., from the image of the axial reticle to the other reticles, and the quotients γ'_1/γ_1 , γ'_2/γ_2 , etc., are formed. The limiting value of these quotients as γ approaches zero is the PM. For a photographic lens free from distortion, the quotient is invariant with respect to the value of γ . For many photographic purposes the distortion is negligible for points distant from the center of the useful field not more than one-fifth of its radius, and consequently it will be very often possible to obtain a sufficiently accurate value of the PM by a single determination of γ and γ' for a point lying near the axis.

5.1.2.15.1.2 *Method 23 — Visual method.* This method is similar to method 22 except that the distances γ' to the aerial images of the reticles are measured directly in the image plane by means of a suitable measuring device. The detailed specification shall state the method used for determining the plane in which the measurements are to be made.

5.1.2.15.2 *Method 24 — Calibrated magnification.* To compute the calibrated magnification, let γ_1 , γ_2 , etc., represent the distances, in the specified image plane, from the axial image point to the images of the object points lying in the object plane at the distances γ_1 , γ_2 , etc., from the axial object point. If m is the paraxial magnification, then in the absence of distortion

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$$\gamma_1 = m\gamma_1, \gamma_2 = m\gamma_2, \dots, \gamma_n = m\gamma_n \quad (24)$$

In the presence of distortion,

$$\gamma_1 = m\gamma_1 + \Delta\gamma_1, \gamma_2 = m\gamma_2 + \Delta\gamma_2, \dots, \gamma_n = m\gamma_n + \Delta\gamma_n \quad (25)$$

The added terms are the values of the linear distortion for the image distances $\gamma_1, \gamma_2, \dots, \gamma_n$, etc., respectively. The values of γ and γ' are measured directly. It is evident that the individual values of distortion defined in the preceding equations can be changed by assigning to m a value different from that given by the paraxial magnification. After the paraxial magnification and the corresponding values of distortion have been determined, an adjusted value is used for the magnification to distribute the distortion in a manner best suited for the intended application. This adjusted value represents the calibrated magnification, or CM.

5.1.2.16 Distortion. All the following methods are capable of measuring distortion in the plane of best definition with accuracy, though care should be taken to correlate the results obtained by methods 28 and 29 with those obtained photographically. Accurate determinations of the distortion at finite magnifications should be made by method 25 or method 30, depending upon the application. Where significant, systematic errors in the test equipment shall be reduced by making a duplicate series of measurements for each test diameter with the lens rotated 180 degrees about its optical axis.

5.1.2.16.1 Method 25 — Target range method. This method is intended primarily for use on lenses mounted in cameras or cones. Targets shall be set up in the object space in a plane perpendicular to the optical axis of the lens to be tested and, for cameras focused for infinity, at a distance greater than D determined by formula (12) in 5.1.1.2. The targets should be placed approximately every $2\frac{1}{2}$ degrees across the entire

field of the lens. The angular separation of the targets shall be determined to an accuracy of ± 2 seconds of arc by means of a first order theodolite. In some instances, the distance between targets and the perpendicular distance from the line of targets to the front node of the lens can be measured and the angles computed. The lens to be tested shall be oriented with its front node directly over the point from which the range angles are to be turned, its optical axis directed toward the central target, and one of its diagonals parallel to the line of targets. A test plate shall be exposed, after which the camera or cone shall be rotated 90 degrees about its optical axis, and another test plate shall be exposed. After processing, the test plates shall be measured on a comparator. The EFL of the lens shall be determined in accordance with method 1; the distortion is determined as specified in 5.1.2.3. Curves shall be plotted (distortion in millimeters against field angle), representing the distortion related to EFL for both sides of the axis for both diagonals. It will usually be found that the curves for the two sides of a diagonal will not have equal distortion. By selecting another point, the "Point of Symmetry," as the center of the field and re-computing the distortion, the curve for each diagonal can be made to be relatively symmetrical. The two sides of each diagonal (four curves in all) shall be averaged to obtain the distortion curve. This distortion curve can be given any desired orientation by using an adjusted value for the focal length (the calibrated focal length, see 5.1.2.3). When required, in addition to setting up the lens as specified, the test plate may be adjusted so that it is perpendicular to the line drawn from the central target through the front node of the lens. This can be done by pointing a telescope, equipped with a Gauss eyepiece, along this line and adjusting the test plate seating surface (with an optical flat and the Gauss eyepiece) until it is perpendicular to the line of sight. The

addition of this step enables one to measure prism angle. When measuring distortion at finite distances the plane of the targets must be parallel to the test plate. Mathematical means for adjusting the measurements may be used to eliminate error from this source. If the distortion is to be measured for an object at a finite distance, the targets shall be set up at the required distance as specified. The test procedure is the same as for the object at infinity, except that the distortion is determined on the basis of paraxial or calibrated magnification.

5.1.2.16.2 Method 26 — Collimator bank method. This method is intended for use with lenses mounted either in cameras or in test barrels. Method 26 is similar to method 25, except that a bank of collimators containing targets shall be used instead of a target range.

5.1.2.16.3 Method 27 — Single collimator photographic method. In some cases where high precision is not required, a single collimator may be used in conjunction with a test plate as in method 26. In this method, either the collimator or the lens and the test plate shall be rotated through the required field angles about the center of the entrance pupil of the lens.

5.1.2.16.4 Method 28 — Nodal slide method. This is a visual test method and may be used, when specified, for lenses mounted in barrels. The lens to be tested shall be properly placed on the nodal slide of an optical test bench and centered so that its optical axis is nearly coincident with the axis of the microscope. Distortion for a particular angle shall be measured by the lateral displacement of the observing microscope required to center the target at each angular setting. At each angle β , the microscope shall be displaced along its horizontal axis by the distance $f(1 - \cos \beta) / \cos \beta$ away from the lens. This refocusing is not necessary if a flat field bar is used. To obtain the value of distortion,

the lateral distance through which the microscope shall be displaced must be divided by the cosine of the angle at which the distortion is being measured. Because of inaccuracies present in most optical benches, it is desirable to make each measurement at the same indicated angle on each side of the axis and to average the two microscope readings obtained before computing distortion.

5.1.2.16.5 Method 29 — Goniometer method. This is a visual method intended for use with lenses mounted in cameras. An accurately calibrated test object on glass, usually in the form of a scale or grid, shall be placed in the plane of best definition of the lens to be tested and illuminated in a direction toward the lens to be tested. This test object must be flat, properly centered, and perpendicular to the optical axis. The lens and illuminated test object shall be placed in the goniometer so that the axis about which the angles are measured passes through the center of the entrance pupil of the lens. The telescope of the goniometer shall be pointed at successive points on the test object and the field angles determined. (The telescope shall not be refocused during the run of measurements.) From the focal length of the lens being tested and the calibration of the test object, the angles subtended by the various points on the test object can be computed. Distortion then can be computed in terms of the difference in angles on the object side and image side; this distortion in turn can be converted into the standard form. (See 5.1.2.3.) By adjusting the focus of the telescope, this method can be expanded to include some cases in which the test object is in a plane corresponding to some finite magnification. Care should be exercised to insure that the cone of light from the test lens is included in the entrance pupil of the telescope.

5.1.2.16.6 Method 30 — Projection method. This method is intended primarily for testing projection lenses. A test object simi-

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lar to the one used in method 29 shall be placed in the object plane of the lens to be tested and projected onto a suitable screen. Measurements shall be made of the projected image of the test object. The distortion shall be computed in terms of the test object. Care should be taken to insure that the screen and test object are perpendicular to the optical axis of the lens and that the test object is flat and properly centered. The cone of light from the projection lamp shall completely fill the projection lens, and the test object shall be uniformly illuminated. The sign of distortion is reversed from theory on projection through a lens and measured at the long conjugate.

5.1.2.16.7 Tangential distortion. Any of the six methods for measuring radial distortion may be modified to measure tangential distortion by considering the displacement of image points perpendicular to a radius from the center of the field. The magnitude of tangential distortion varies from zero along one diameter to a maximum along an orientation 90 degrees to the diameter of zero distortion. Therefore, when required, tangential distortion shall be measured for two axial orientations of the lens, and the orientation of maximum tangential distortion computed.

5.1.2.17 Prism effect. To measure the prism effect in terms of a thin equivalent prism of vertex angle α , use is made of the fact that oblique rays are deviated by the prism more than, and in the same direction as, the axial ray. An assumption is made that the axial ray makes only a small angle with the normal to the surface of the prism (or the prism may be assumed to be in the minimum deviation for the axial ray). If the camera under test is used to photograph three collimators or distant targets, one axial and the other two making angles $+\beta$ and $-\beta$ with the axis, the distances from the 0 degree image to the $+\beta$ image and from the 0 degree image to the $-\beta$ image

are different in the presence of a prism effect. This difference is measured on the negative. Under the assumptions made, the analytical expression for this difference is:

$$\Delta = f[\tan(\beta + e) - \tan(\beta - e) - 2 \tan e_0] \quad (26)$$

where f is the equivalent focal length of the lens, e is the deviation of the ray making β with the axis (within a close approximation the deviation is the same for $+\beta$ and $-\beta$), and $e_0 = \alpha/2$ is the deviation of the axial ray. Tables for Δ can be computed for various values of f , β , and α . The measured and tabulated values of Δ are compared, and the corresponding α is evaluated.

5.1.2.18 Spherical aberration.

5.1.2.18.1 Method 31 — Annual ring or Hartmann disk method. When spherical aberration is specified in terms of change in focal position for zones of different radii, a Hartmann disk (a plate covering a front of the lens with holes at the different zones) or aperture consisting of open annular rings will be placed over the front of the lens and properly centered. Either a photographic or visual method of determining the difference in focal positions for different zones may be used. Various modifications of these methods and other methods may be employed, such as a knife-edge test or interferometric method. When measuring spherical aberration for an object at infinity, the target which is imaged by the test lens may be placed in a collimator or a distance at least 25 times the focal length of the lens to be tested.

5.1.2.18.2 Method 32 — Stopped-aperture method. When spherical aberration is specified in terms of the difference between the best focus at maximum aperture and at a designated reduced aperture, a nodal slide optical bench or an autocollimation method may be used to determine the difference in

these focal positions. A focusing microscope provided with a scale indicating distance along the axis of the microscope may also be used. The target which is imaged by the test lens may be placed either in a collimator or at a distance at least 25 times the focal length of the lens to be tested. (In the latter case the EFL or BF of the lens is the conjugate object distance.)

5.1.2.19 Veiling glare.

5.1.2.19.1 *Method 33 — Photographic black spot method.* Veiling glare may be measured by means of an apparatus photographing the test field as specified herein. The test field shall consist of a bright Lambert's law surface containing a perfectly black spot. For the purposes of this test, a perfectly black spot will be one whose luminance is not greater than 1/100 of the luminance of the bright surface when measured from the position of the lens. The black spot shall be circular, and, except as noted below, its diameter shall subtend an angle of 1 degree \pm 5 minutes at the lens under test. For testing lenses of types I, II, III, and V (or cone and camera assemblies with these lenses), the bright field shall be of an infinite extent. This may be provided by a large integrating box of uniform luminance within an angle of 2π steradians. For testing lenses of other types (or instruments with these lenses) the bright field shall be limited to the field to be covered in actual use. The spectral distribution of light coming from the bright field shall be equal to daylight (for types III and V lenses), or may be modified by a yellow filter (for types I and II lenses), or be equivalent to the light from a source which is a gray body at 2848° K (for lenses and instruments normally used with a tungsten source). For instruments which are not normally used with the sources specified above, the bright field shall have a spectral distribution similar to that of the source used with the instrument. There shall be no substance other than air between the test field

and the lens or its attached filter. For testing lenses (or lens-cone and lens-camera assemblies) used to photograph distant objects, the black spot must be at a distance from the lens not shorter than 10 times its focal length. For lenses used with relatively short object distances, the black spot shall be at the normally used distance from the lens. For testing cameras that permit easy focusing or instruments used with short object distances, the image of the black spot shall be sharply in focus in the film (or paper) plane of the camera or of the instrument, respectively. For testing lenses of lens-cone assemblies which have no focusing mechanism, the test apparatus shall be provided with a movable film holder for sharp focusing of the image of the black spot. If the focal length of the lens is too short to produce an image of at least 1 millimeter diameter with the 1-degree black spot, the black spot shall be increased in size so that the diameter of its image becomes approximately, but not less than, 1 millimeter. In lens-camera assemblies focused for infinity and having no focusing adjustment, the image of the black spot will be necessarily out of focus in the focal plane of the camera. The image will have a dark center where there are no out-of-focus rays from the bright field, provided that the diameter of the black spot is greater than the aperture of the lens under test. The 1-degree black spot shall be at such a distance from the lens that the diameter of the dark center of the out-of-focus image shall be approximately, but not less than, 1 millimeter. The required distance becomes infinity for a lens of 57.3 mm focal length and it still may be too great for a practical instrumentation with lenses of somewhat longer focal lengths. For lenses of focal lengths shorter than 57.3 mm, the requirement of 1 millimeter image diameter cannot be met with the 1-degree spot at any real distance. In these cases, the black spot shall be increased in size and placed at such a distance that the diameter of the dark center of the out-of-focus image

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shall be approximately, but not less than, 1 millimeter, and the outside diameter of the out-of-focus image shall be not greater than 2 millimeters. When the 1-degree black spot is used, measurements shall be made of the illuminance in the dark center of the image of the black spot and of the illuminance in the image of the bright field at 1 degree 30 minutes from the center. In the cases where a larger black spot must be used, the illuminance of the image of the bright field shall be measured at 1.5 millimeters from the center of the image of the black spot. In either case the value of the illuminance of the image of the bright field shall be the mean of two measurements taken at the specified distance on the opposite sides of the dark image. Photographs of the test field shall be made on the emulsion to be used with the instrument. (Light scattered back into the instrument by the emulsion can contribute significantly to veiling glare. Hence, any test method must provide a reflecting surface similar to the unexposed emulsion over practically the entire film plane.) Measurements shall be made at full aperture, and any other aperture specified, with the black spot on axis and at other positions in the field of the instrument, including positions near the edges and corners of the field. Any area which may be affected by reflections from asymmetrical structures between the object plane and the film plane shall be investigated. The percent veiling glare shall be calculated for each position in the field, and variations of veiling glare with position in the field shall be presented in a table or graph for each aperture tested. Any significant asymmetries shall be recorded. A well-controlled method of photographic photometry shall be used to obtain the ratio of the illuminances of the image of the black spot and the adjacent image of the bright field. One of the methods is to use a density step-wedge. This shall be placed over the image of the bright field adjacent to the image of the black spot, and a photograph of the test field shall be

taken. Densitometric readings shall be made on the image of the black spot and on the images of the two steps which produced the nearest higher and lower densities than the density of the image of the black spot. By interpolation, the density necessary in the step-wedge to produce the density of the image of the black spot shall be found. This density of the step-wedge is equal to the logarithm of the ratio of illuminances of the bright surround (E_s) and of the image of the black spot (E_b). The veiling glare is then computed as:

$$V = 100 \frac{E_s}{E_b} \% \quad (27)$$

5.1.2.19.2 Method 34 — Photographic black strip method. The apparatus and procedure used in this method are the same as in method 33, except that a black strip is used instead of a black spot. The limitations imposed on the width and distance of the black strip are the same as specified for the diameter of the black spot. The length of the strip shall subtend at the lens the maximum total angle to be covered by the lens in actual use. Measurements shall be made along the image of the black strip at various distances off axis up to the maximum angle covered by the lens to find the distribution of veiling glare across the field. In the case when an out-of-focus image of the black strip must be used for testing, some out-of-focus rays from the bright field will pass through certain areas at the ends of the image of the black strip. The extent of these areas shall be determined, and they shall not be used for measurements.

5.1.2.19.3 Method 35 — Photoelectric method. This method uses the same apparatus of methods 5 and 6, except that a light-sensitive measuring device of spectral sensitivity characteristics similar to those of the sensitive photographic material, which is normally used with the lens under test, shall

be used in the image plane of the test apparatus.

5.1.2.20 Condenser performance. The condenser shall be set up to simulate the equipment in which it is to be used, and the image of a designated format shall be projected on a screen. The uniformity of screen illuminance and total light output shall be measured with a foot-candle meter and shall be as designated for the particular application.

5.1.2.21 Beauty defects. When inspecting for scratches and digs, a reference standard glass containing graded scratches and digs used as a guide shall be used. The acceptance standards on all beauty defects shall be determined by the individual application.

5.1.2.22 Centration. When inspecting lenses for errors in centration, compliance with the requirements on resolving power, tangential distortion, and prism effect shall be of primary consideration. The lens examined should be tested across a field diagonal which gives the lowest resolution or maximum tangential distortion, whichever is the most important considering the use for which the lens is intended. Routine inspection, based on off-axis star images, may be substituted for photographic methods when properly correlated.

Copies of specification, standards, drawings, and publications required by contractors in connection with specific procurement functions should be obtained from the procuring activity or as directed by contracting officer.

Copies of this standard for military use may be obtained in the foreword to the Index of Military Specifications and Standards.

Copies of this standard may be obtained for other than official use by individuals, firms, and contractors from the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C.

Notice. When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Preparing activity:
Air Force

Other interest:
International

Other custodians:
Army—Signal Corps
Navy—Bureau of Aeronautics

APPENDIX

10. REFERENCE MATERIAL

10.1 GENERAL. The material covered in this appendix does not form a part of this standard. It is provided, primarily, as reference material for assistance in the procurement and inspection of photographic lenses. Suggestions concerning requirements related to some mechanical details and other features are given. A reference list intended for use by those preparing specifications and procurement documents is also provided.

10.2 LENS MOUNTING, AND OTHER REQUIREMENTS.

10.2.1 Mounted in a cell. When specifying members mounted in a cell for a multiple cell lens (usually two cells, front and rear) the following details should be specified:

- a. Cell separation or the correct shoulder-to-shoulder mounting distance (sometimes called barrel length) should be supplied with each lens by the manufacturer.
- b. Dimensions and details of the cells.
- c. Dimensions and details of the mounting parts (threads, etc.).

10.2.2 Mounted in a barrel. When specifying a lens mounted in a barrel the following details should be specified:

- a. Length of the threaded portion of the barrel.
- b. Whether barrel shall be furnished with a threaded ring. If threaded ring is required, dimensions and details such as mounting holes or means of securely setting at any position along the threaded portion of the barrel.
- c. Whether barrel shall be provided with a fixed flange. If flange is required,

ed, dimensions and details such as mounting holes.

10.2.3 Mounted in a shutter. When specifying a lens mounted in a shutter the following details should be specified:

- a. Requirements of shutter (speeds, efficiency, etc.).
- b. Methods of attaching shutter to camera.
- c. Dimensions and details of shutter.
- d. Threads (if required) for attaching lens to shutter and shutter to camera.
- e. Special shutter features (self-timer, synchronizer, etc.).

10.2.4 Mounted in a cone. When required, a lens, may be mounted in a lens cone. When required, the following details should be specified:²³

- a. Details and dimensions of the cone-camera seating surface.
- b. Distance from cone-camera sealing surface to focal plane.
- c. Focusing means within the cone.
- d. Mechanical details and dimensions of the cone adapter.²⁴
- e. Any additional mechanical details and dimensions deemed necessary.

10.2.5 Mounted in a focusing mount. When specifying a lens mounted in a focusing mount the following details should be specified:

²³ In those cases in which the rear surface of the cone and focal plane coincide (for example, cartographic cameras), details concerning attachment of the cone to camera should be supplied.

²⁴ A cone adapter is defined as a detachable part of the cone which may be replaced to provide for using the cone on different cameras.

- a. Flange focal distance (see 3.1.7).
- b. Range of focus and accuracy of scale.
(See C in 4.1.5.3.)
- c. Whether or not the lens may rotate when focusing.
- d. Whether or not the lens may focus by separation of the members.
- e. Method and details concerning the mounting of the focusing posts.
- f. Dimensions and details of the mounting surface.
- g. Other mechanical details and dimensions deemed necessary.

10.2.6 Diaphragm. When specifying a lens which is mounted in a barrel, in a cone, in a focusing mount or shutter, which requires a diaphragm, the following details should be specified:

- a. Type of diaphragm (iris or other, number of leaves, etc.).
- b. Dimensions and details.
- c. Type of marking and calibration (f-stop, T-stop, aperture ratio).
- d. Related features (click stops, diaphragm control in the form of a ring gear for remote control, total angular travel and angle corresponding to each stop marking, limit stop to prevent closing to too small an aperture, etc.).

10.2.7 Statistical data and quality control. When required, it may be specified that the contractor shall supply to the procuring activity, a detailed record of the statistical facts concerning specified attributes and variables. These quality records should include lot sizes, sampling size, Acceptable Quality Levels, acceptance and rejection numbers, incidence of defectives, and other pertinent data such as quality control charts on attributes and variables affecting final

performance and installation. When required, the classification of defects should be as specified. Sampling requirements should be clearly stated in the specification or procurement document and should be in accordance with MIL-STD-105.

10.2.8 Number of lenses to be destroyed. The specification or procurement document should clearly state the number or percent of a given order to be given any destructive tests.

10.2.9 Packaging. Detail packaging requirements should consider the type and size of lens to be packaged as well as its intended destination.

10.2.10 Markings. Details concerning the extent to which a lens should be marked and the manner of marking the packages should be given in the specification or other procurement document.

10.3 ORDERING DATA REFERENCE LIST.

10.3.1 Reference list. When preparing specifications or other procurement documents, the following reference list should be used. The first four items are identification requirements which govern, in general, the nature of the lens and provide a limited description. The remaining items concern performance characteristics, physical and mechanical features, markings, testing, and packaging. "R" under a particular lens type signifies that requirements concerning this feature are required to be specified. "O" signifies that consideration of this feature is optional. "A" signifies that additional technical details are required in the specification to make proper use of this feature. "X" implies that this item is not usually applicable to the lens.

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	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV
Type required and use (See 1.2)	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Equivalent focal length (See 3.1.4 and 4.1.5)	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Maximum relative aperture or T-stop (See 4.1.3)	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Field of view (See 3.5)	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Construction of lens (See 3.3)	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Calibrated focal length (See 3.1.5)	O	O	O	OA	O	OA	OA	OA	X	X	X	OA	OA	O
Back focal distance (See 3.1.6)	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Flange focal distance (See 3.1.7 and 3.4.6)	R	R	O	O	R	O	O	O	O	O	X	O	O	O
Front focal distance (See 3.1.8)	O	O	O	O	O	O	O	O	O	O	X	O	O	O
Front vertex back focal distance (See 3.1.9)	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Front operating aperture (See 3.2.7)	O	O	O	O	O	O	O	O	O	O	X	O	O	O
Rear operating aperture (See 3.2.8)	O	O	O	O	O	O	O	O	O	O	X	O	O	O
Resolving power (See 3.6.2) ..	R	R	R	R	R	R	R	RA	R	R	X	R	R	R
Area weighted average resolution (See 3.6.2.5)	R	R	R	O	R	O	O	O	O	X	X	R	O	R
Astigmatism and curvature of field (See 3.6.3)	O	O	O	O	O	O	O	O	O	O	X	O	O	R
Color correction (See 3.6.4) ..	R	R	R	R	R	R	R	R	R	O	O	R	R	R
Radial distortion (See 3.6.6 and 3.6.6.1)	O	R	O	R	O	O	O	O	O	O	X	O	O	O
Tangential distortion (See 3.6.6.2)	O	R	O	O	O	O	X	O	X	X	X	O	O	O
Prism effect (See 3.6.6.5) ...	O		O	O	O	O	X	O	X	X	X	O	O	O
Relative Illumination (See 3.6.7)	R	R	R	R	R	RA	RA	RA	O	O	X	RA	R	R
Transmittance (See 3.6.9) ...	O	O	O	O	O	O	O	O	O	O	O	O	O	R
Area weighted average T-number (See 3.2.6.1) ...	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Spherical aberration (See 3.6.5)	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Other aberrations	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Veiling glare (See 3.6.10) ...	O	O	O	O	O	O	O	O	O	O	X	O	O	O
Condenser characteristics (See 3.6.11)	X	X	X	X	X	X	X	X	X	X	R	X	X	X
Mounting	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Diaphragm requirements (See 3.4.4 and 10.1.6)	O	O	R	R	R	R	O	O	R	X	X	R	R	R
Waterhouse stops (See 3.4.4) ..	X	X	X	R	X	O	X	X	X	X	X	O	O	O
Lens Markings (See 4.1.1) ..	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Intermediate aperture marking (See 4.1.4.3)	O	O	O	O	O	O	O	O	O	O	X	O	O	O

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV
Accuracy of focusing scales (when required) (See 4.1.5.3)	RA	X	RA	RA	RA	OA	X	X	X	X	X	RA	RA	O
Reflection reducing coatings (See 3.7.2)	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Beauty defects (See 3.8)	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Environmental (See 3.7.3) ..	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Finish and internal surfaces (See 3.7.5)	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Where inspected	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Sampling plan	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Statistical data required (See 10.1.7)	R	R	R	R	R	R	R	R	R	R	R	R	R	R
What individual 100 percent tests (See 5.1)	R	R	R	R	R	R	R	R	R	R	R	R	R	R
What sampling tests (See 10.1.8)	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Films and processing (See 5.1.1.5 and 5.1.2.12.1)	R	R	R	R	R	R	X	R	R	X	X	R	R	R
Plane of best definition (See 5.1.2.1)	R	R	R	R	R	X	R	R	R	X	X	R	R	R
Method of measuring equivalent focal length (See 5.1.2.2)	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Method of measuring effective aperture (See 5.1.2.9)	R	R	R	R	R	R	R	R	R	O	X	R	R	R
Method of measuring T-number and transmittance (See 5.1.2.10)	O	O	O	O	O	O	O	O	O	X	X	O	O	O
Method of measuring relative illumination (See 5.1.2.11) ..	R	R	R	R	R	RA	RA	RA	O	O	X	RA	R	R
Method of measuring resolving power (See 5.1.2.12)	R	R	R	R	R	R	R	R	R	R	X	R	R	R
Target distance (See 5.1.1.3) ..	O	O	O	O	O	O	O	O	O	O	X	O	O	R
Target contrast and whether dark lines on light background or vice versa (See 5.1.1.7)	R	R	R	R	R	R	R	R	R	R	X	R	R	R
Whether lens is to be tested with filter in place or over light source (See 5.1.1.4) ..	R	R	R	R	R	R	R	R	R	R	X	R	R	R
Relative aperture for resolving power test (See 5.1.2.12) ..	R	R	R	R	R	R	R	R	R	R	X	R	R	R
Angular settings for resolving power images (See 5.1.2.12) ..	R	R	R	R	R	R	R	R	R	R	X	R	R	R
Magnification for reading resolving power (See 5.1.2.12) ..	R	R	R	R	R	R	R	R	R	R	X	R	R	R
Method of measuring astigmatism and curvature of field (See 5.1.2.13)	O	O	O	O	O	O	O	O	O	O	X	O	O	O
Method of measuring chromatic aberrations (See 5.1.2.14)	O	O	O	O	O	O	O	O	O	X	X	O	O	O

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	I	II	III	IV	V	VI	VII	VIII	XI	X	XI	XII	XIII	XIV
Method of measuring distortion (See 5.1.2.16)	O	R	O	R	O	O	O	O	O	O	X	O	O	O
Method of measuring spherical aberration (See 5.1.2.18) ..	O	O	O	O	O	O	O	O	O	O	X	O	O	O
Method of measuring veiling glare (See 5.1.2.19)	O	O	O	O	O	O	O	O	O	O	X	O	O	O
Method of measuring beauty defects (See 5.1.2.21)	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Environmental tests	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Preservation	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Unit Packaging	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Exterior packing	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Cushioning	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Overseas packing	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Domestic packing	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Package marking	R	R	R	R	R	R	R	R	R	R	R	R	R	R

10.4 REFERENCES.

10.4.1 List of nonmandatory references.

The following lists are for information only, and are not to be considered applicable to this standard in any other sense. These documents will not be supplied by the procuring activity.

10.4.1.1 American Standards Association.

PH3.10-1954 — Threads for Attaching Mounted Lenses to Photographic Equipment.

PH3.12-1953 — Attachment Threads for Lens Accessories, Specifications for.

PH3.14-1944 — Front Lens Mounts for Cameras, Dimensions of.

PH3.16-1947 — Resolving Power of Lenses for Projectors for 35-mm Slide Film and 2 x 2-Inch Slides, Method for Determining.

PH3.20-1955 — Focusing Camera Lenses, Distance Scales for.

PH3.25-1948 — Parts of a Photographic Objective Lens, Nomenclature for.

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MILITARY STANDARD

PHOTOGRAPHIC LENSES

TO ALL ACTIVITIES:

1. The following page of MIL-STD-150A has been revised and supersedes the page listed.

NEW PAGE**DATE****SUPERSEDED PAGE****DATE****29****8 June 1961****29****12 May 1959**

2. Retain this notice and insert before the table of contents.

5.1.2.12.3 Method 14 — Projected photographic resolving power. This test is intended to be used primarily for enlarging lenses (type VI). A target plate of the required size containing resolving power targets (light lines on a dark background) and of the required range, and located as shown in Figure 8, with one set of the lines in tangential and the other set in radial direction, shall be placed in the object plane (film plane) of the lens to be tested. The targets shall be of high contrast. The target plate shall be evenly illuminated by light from a condensing source. If required, the light shall be filtered to the color required by placing a filter between the light source and the target plate. With the optical axis of the lens perpendicular to the target plate, the lens shall be focused at the designated magnification and aperture, and an exposure made on the designated photosensitive material. The photosensitive material shall be held flat in a plane perpendicular to the optical axis of the lens. The correct exposure shall be that which gives the maximum resolution at position B of Figure 8. The test plate is processed in the required manner. The resolving power shall be read by observing the dry test plate under suitable magnification. The figures referred to in measuring resolving power by this method are the lines per millimeter on the target plate. It is recommended that enlarging lenses be tested at a magnification of 1:2 using medium contrast glossy chlorobromide paper processed 1½ minutes in D72 developer, diluted 1:2 at 68° F.

5.1.2.12.4 Method 15 — Projected visual resolving power.²² This test is intended to be used primarily for projection lenses (type VII). A test object of the required size containing high contrast resolving power targets (dark lines on light background) of the required range and placed as shown in Figure

²² American Standard Method for Determining Resolving Power of Lenses for Projectors for 35-mm. Slides Film and 2 x 2-inch Slides, FED .16-1947 (Revised 1952).

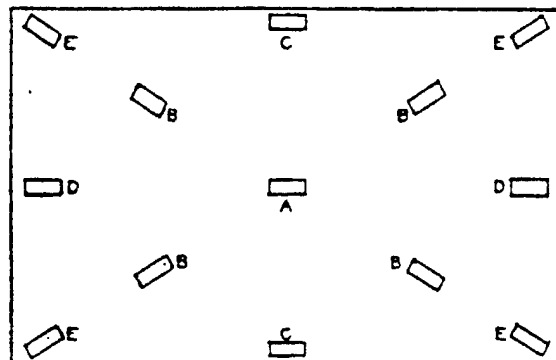


FIGURE 8. Projected Resolving Power Test Plate

under test upon a matte, white, grainless screen. This screen shall be located at such a distance from the projector that unless otherwise specified the long dimension of the projected image will be at least 40 inches in order that the observer will have no difficulty in distinguishing the number of lines resolved. The resolving power of the lens at any point in the field is the largest number of lines per millimeter in the test object that an observer, close to the screen, sees definitely resolved (easily counted) in both radial and tangential directions in the projected image. Care shall be taken to insure that the screen is perpendicular to the optical axis of the projection lens, and that the lens is focused so that the image at the center of the test plate has maximum contrast. The projector used in this test may be a regular production model or a special test projector. The glass test object shall be flat and held concentric with and normal to the optical axis of the projection lens. The cone of light from the projection lamp through a condensing system shall completely fill the entrance pupil of the projection lens. The test object shall be uniformly illuminated.

5.1.2.13 Astigmatism and curvature of field.

5.1.2.13.1 Method 16 — Resolving power target method. By means of any of the methods for measuring resolving power specified in methods 11 through 15, resolving power

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shall be determined for different positions of the test plate in the image space. The test plate or plates are exposed in small steps, at different distances along the optical axis of the lens. The length of each step depends upon the corrections, focal length, and aperture of the lens being tested. A sufficiently large number of steps shall be taken to insure at least three steps on each side of the best focus position for both radial and tangential lines at any angular position. Upon reading the targets, the position of best focus shall be determined (for radial and tangential lines separately) at which the resolution is a maximum at each angular setting. These focus positions are plotted against angular settings, and two curves representing the two image surfaces are obtained. The curve representing curvature of field is a median drawn between the two curves representing the image surfaces. (See 3.6.3.) The astigmatic difference is obtained by taking the difference in the focal setting at a specific angle for the two image surfaces.

5.1.2.13.2 Method 17 — Nodal slide method. This method may be used in lieu of method 16. In this method the lens to be tested shall be set up in front of a suitable collimator equipped with a target containing vertical and horizontal lines and centered so that the optical axis is parallel to the collimator axis and coincident with the axis of the observing microscope. The lens shall be moved along the microscope axis until the axis of rotation of the nodal slide intersects the rear node. The microscope shall be focused on the axial image and the position of the microscope noted. The lens shall then be rotated about the axis through the rear node and perpendicular to the optical axis of the lens. At multiples of angular positions of $1\frac{1}{4}$ degrees out to the edge of the field, the microscope shall be separately focused on the radial and tangential lines. The focal change from the axis position shall be noted at the angular field positions for the radial and tangential lines. To obtain curves such as

specified in method 16, the factor $f(1 - \cos \beta) / \cos \beta$ is subtracted from the microscope settings, and this difference is multiplied by the $\cos \beta$. If a flat field bar is used at the microscope it is not necessary to subtract the factor $f(1 - \cos \beta) / \cos \beta$. When curves are obtained, the procedure for determining the curvature of field is the same as that in method 16.

5.1.2.14 Color correction. When the image quality is found satisfactory on the basis of other applicable tests, the color correction can also be considered as satisfactory. Direct measurements of color corrections may be needed when some special color requirements are to be met. These measurements may be specified in terms of minimum resolving power or limits on individual color corrections.

5.1.2.14.1 Longitudinal chromatic aberration.

5.1.2.14.1.1 Method 18 — Photographic method. Photographic resolving power measurements shall be made as specified in method 11 or 12, utilizing light of the colors designated, repeating the test for each color. The light used may be supplied by a monochromator or it may be filtered white light, as specified. The focus positions at which the maximum resolving power (AWAR unless otherwise specified) is obtained shall be determined for each color. The longitudinal color aberration for a particular color is the difference in focal setting for this color and white light, or for this color and a specified color. When the focal setting for the first color is greater than the focal setting for the reference color or white light, the longitudinal chromatic aberration is said to be positive. Generally, the reference color should be towards the red end of the spectral range under consideration.

5.1.2.14.1.2 Method 19 — Nodal slide method. When specified, a nodal slide optical

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28 January 1963

MILITARY STANDARD

PHOTOGRAPHIC LENSES

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1. The following pages of MIL-STD-150A have been revised and supersede the pages listed:

New page	Date	Superseded page	Date
3		3	12 May 1959
4		4	12 May 1959
5		5	12 May 1959
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10		10	12 May 1959
17		17	12 May 1959
22		22	12 May 1959
24		24	12 May 1959
26		26	12 May 1959
27		27	12 May 1959
34		34	12 May 1959

2. The following is a cumulative list of earlier changes:

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4. Holder of MIL-STD-150A will verify that page changes indicated above have been entered and will destroy the previous notice. Activities which stock these notices for issue are warned that each notice, together with its appended revised pages, is in effect a separate publication to be retained until the military standard is completely revised or canceled.

3.1.2.2.1 When a lens is supplied in cells, without barrel or shutter, the locating surface of the lens mount is defined as the seating surface of the rear cell.

3.1.3 *Mechanical axis.* The mechanical axis of a lens is that continuous straight line in space perpendicular to the plane of the flange or locating surface of the lens mount and passing through the center of symmetry of the flange or locating surface.

3.1.3.1 *Flange tilt.* The flange tilt of a lens is the angle between the optical axis and the mechanical axis.

3.1.3.2 *Plane of the receiver.* The plane of the receiver is that plane in the image space in which the receiver or the film in a camera is located.

3.1.3.2.1 *Focal tilt.* The focal tilt is the angle between the plane of best definition and the plane of the receiver due to the mechanical structure between the lens flange and the receiver. It is not a true characteristic of the lens alone.

3.1.4 *Equivalent focal length.*¹ The equivalent focal length, or EFL, often referred to more simply as the focal length, determines the scale of the image produced by the lens. When a given object is at an infinite distance, images produced by distortionless lenses of the same equivalent focal length will be equal in size, and images produced by lenses of different equivalent focal lengths will vary in size directly as the respective equivalent focal lengths. The equivalent focal length is defined by the equation:

$$\text{EFL} = \frac{\gamma}{\tan \beta} \quad (1)$$

$\beta \neq 0$

¹ American Standard Method of Designating and Measuring Focal Lengths and Focal Distances of Photographic Lenses. Z39.4.21 — 1948.

where γ is the transverse distance from the principal focus to the center of the image in the image-space focal plane of an infinitely distant object point which lies in a direction making an angle β with the optical axis. The equivalent focal length shall be measured in accordance with 5.1.2.2.

3.1.5 *Calibrated focal length.*² The calibrated focal length, or CFL, is defined as an adjusted value of the equivalent focal length of a lens mounted in a camera or cone, so chosen as to distribute the distortion in the manner best suited to conditions under which the photograph is to be employed. The calibrated focal length shall be determined in accordance with 5.1.2.3. The calibration conditions shall be covered by the detailed specification.

3.1.6 *Back focal distance.* The back focal distance, or BF, is defined as the distance measured from the vertex of the back surface of the lens to the plane of best definition. The back focal distance shall be measured in accordance with 5.1.2.4.

3.1.7 *Flange focal distance.* The flange focal distance, or FD, is defined as the minimum distance from the center of symmetry of the lens flange in the plane of the flange to the plane of best definition. In a perfect lens, this distance is measured along the mechanical axis which coincides with the axis of best definition. The flange focal distance shall be measured in accordance with 5.1.2.5.

3.1.8 *Front focal distance.*² The front focal distance, or FF, is defined as the distance measured from the principal focus located in the front space to the vertex of the front surface. The front focal distance shall be measured in accordance with 5.1.2.6.

3.1.9 *Front vertex back focal distance.*³ The

² See footnote 1.

³ See footnote 1.

front vertex back focal distance, or FVD, is defined as the distance measured from the principal focus in the back space to the vertex of the front surface. The front vertex back focal distance shall be measured in accordance with 5.1.2.7.

3.1.10 Telephoto ratio. The telephoto ratio is defined as the direct ratio of the equivalent focal length to the front vertex back focal distance.

3.1.11 Depth of focus and depth of field. For every plane in the object space, a photographic lens produces an image plane of best definition in the image space. In front of or behind this plane of best definition is a region within which the images of the selected object plane are of satisfactory quality. The distance separating the focal planes bounding this region is the depth of focus for the selected object plane. Similarly, there exists a region in space within which objects are imaged with satisfactory quality on a selected image plane. The distance separating the planes bounding this region is the depth of field. The extent of these regions of satisfactory focus may be defined in terms of a 10 percent reduction of area weighted average resolution (AWAR) below that obtained at the best focal position.

3.2 APERTURE AND RELATED QUANTITIES.

3.2.1 Lens speed. Lens speed is that property of a lens which affects the image illuminance. Lens speed shall be specified in terms of the following expressions: aperture ratio, relative aperture, or T-stop.

3.2.2 Aperture ratio.⁴ The aperture ratio is the ratio 1:N or the fraction 1/N (written in this manner with the first member of the ratio, or the numerator of the fraction.

⁴ American Standard Methods of Designating and Measuring Apertures and Related Quantities Pertaining to Photographic Lenses, Z38.4.20 - 1948.

equal to 1) where N is defined by the equation:

$$N = \frac{1}{2n \sin \alpha}$$

In this formula, n is the index of refraction of the medium in which the image is formed (approximately 1, if the image is formed in the air) and α is the angle subtended at the axial point of the image by the semidiameter of the exit pupil of the lens at a given diaphragm setting. If the exit pupil is not circular, the equivalent circle having the same area as the actual exit pupil should be used. Thus, for an objective in air, the aperture ratio is equal to $2 \sin \alpha$. If the aperture ratio is given without qualification, its value is that corresponding to the largest indicated diaphragm opening and an infinitely distant object. If the object is at a finite distance, the value of the aperture ratio should be qualified by a statement of the corresponding magnification. The aperture ratio is applicable for the determination of exposure time when the object is at an infinite or a finite distance. For any magnification, the exposure time is inversely proportional to the square of N. Thus, the aperture ratio is a measure of the image illuminance. (For test procedure see 5.1.2.8).

3.2.3 Effective aperture.⁵ The effective aperture of a photographic objective for distant objects, for a given setting of the diaphragm, is an opening equivalent to a right section of the largest beam of parallel light from an axial object point that is transmitted by the lens. It is usually circular, or approximately so, and is specified by its diameter. If the section is not circular, the effective diameter shall be the diameter of a circle having the same equivalent area. (For test procedure, see 5.1.2.9.)

3.2.4 Clear aperture.⁵ The clear aperture of each surface in a lens system is the maxi-

⁵ See footnote 4.

imum clear opening of the surface which is actually used in forming an image in any part of the field. The mount aperture at each surface shall be at least as large as the clear aperture in order that vignetting will not exceed the computed value. The clear aperture is usually circular and specified by its diameter. It is sometimes referred to as the free aperture.

3.2.5 Relative aperture.⁵ The relative aperture shall be defined as the ratio of the EFL to the diameter of the effective aperture. The symbol for relative aperture shall be $1/f$ followed by a numerical value. It is written as a fraction, for example, $f/2$ signifies that the diameter of the effective aperture is one-half the focal length. For an object at an infinite distance, the denominator of the relative aperture and the second member, N , of the aperture ratio are identical, provided the image is formed in air and the imagery obeys the sine condition.

3.2.5.1 f -number.⁶ The f -number shall be defined as the denominator in the expression for the relative aperture. Thus, if the relative aperture is $f/2$, the f -number is 2.

3.2.6 T-stop and T-number.⁷ The T-stop is referred to as the aperture of a lens calibrated photometrically and assigned a T-number, which is the f -number of a circular opening in a fictitious lens having 100 percent transmittance, and which gives the same central image illuminance as the actual lens at the specified stop opening. Hence, for a lens with a circular aperture, the

$$\text{T-number} = \frac{\text{f-number}}{\sqrt{t}} \quad (3)$$

where t is the transmittance. For a lens with an effective aperture of any shape and area

A, the corresponding formula is:

$$\text{T-number} = \frac{f}{2} \sqrt{\frac{\pi}{At}} \quad (4)$$

The transmittance of the lens shall be defined as the ratio of the transmitted light flux to the incident light flux. The symbol for the T-stop shall be T followed by a space and a numerical value — for example, T 2. The numeral 2 represents the T-number. (For test procedure, see 5.1.2.10.)

3.2.6.1 Area weighted average T-number. The T-number as defined in 3.2.6 is a comparative measure of illuminance on the axis of a lens. Since the illuminance usually varies over the field, a need may exist for determining T-numbers for off axial image points and computing an average T-number. In accordance with the basic photometric relationships involved, the general definition of T-number is given as

$$T_i = \frac{1}{2} \sqrt{\frac{\pi B/E_i}{\pi B/E_0}} \quad (5)$$

Since, in accordance with this definition,

$$\frac{1}{2} \sqrt{\pi B} = T_0 \sqrt{E_0}$$

$$T_i = T_0 \sqrt{\frac{E_0}{E_i}} \quad (6)$$

In these expressions, T_i is the T-number for an image point in a zone i , T_0 is the axial T-number, B is the object luminance, E_0 is the illuminance on the axis, and E_i is the average illuminance for the zone. Compatible units should be used for quantities B , E_0 , and E_i . When the illuminance is averaged over the field, weighting the average by the area of the circular zone in which the illuminance is determined, and this average is substituted for E_i in equation (6), the resulting T-number is called the area weighted average T-number, or AWAT. For circular zones which extend beyond the boundaries of the

⁵ See footnote 4, page 4.

⁶ See footnote 4, page 4.

⁷ American Standard, Aperture Calibration of Motion Picture Lenses PH22.90 - 1963.

picture format, only the area lying within the format shall be used in determining the weighting ratios. The equations for computing AWAT are:

$$AWAT = T_o / \sqrt{\sum \frac{A_i E_i}{A E_o}} \quad (7)$$

$$r AWAT = 10 T_o / \sqrt{\sum \frac{A_i}{A} \sigma_i} \quad (8)$$

in which A is the total area of the picture format, A_i is the area of a particular zone, and σ_i is the average relative illuminance for that zone expressed in percent.

3.2.7 Front operating aperture. The front operating aperture is defined as the limiting aperture at the front of the lens. It will usually be given as the maximum diameter of the entrance cone at the front vertex for the specified field of view at infinity focus.

3.2.8 Rear operating aperture. The rear operating aperture is defined as the limiting aperture at the rear of the lens. It will usually be given as the maximum diameter of the emergent cone at the rear vertex for the specified field of view at infinity focus.

3.3 CONSTRUCTIONAL FEATURES. Pertinent features include details of the construction of the lens. These may relate to the physical configuration, or arrangement of the individual elements, to some specified optical characteristic or to the nomenclature of the various parts. Constructional features of photographic lenses are listed with definitions and explanatory data.

3.3.1 Optical system.⁸ The optical system includes all the parts of a photographic lens and accessory optical parts which are designed to contribute to the formation of an image on the photographic emulsion or on a screen for viewing.

⁸ American Standard Nomenclature for Parts of a Photographic Lens PHA.25 — 1948.

3.3.2 Member.⁸ A member of a photographic lens is a group of parts considered as an entity because of the proximity of its parts or because it has a distinct but not always entirely separate function.

3.3.3 Component.⁸ A component of a photographic lens is a subdivision of a member. It may consist of two or more parts cemented together or with near and approximately matching surfaces.

3.3.4 Element.⁸ An element of a photographic lens is a single uncompounded lens, i.e., a part constructed of a single piece. The total number of elements is a significant constructional feature of a lens.

3.3.5 Front of photographic lens.⁸ The front of a photographic lens, in general, is the end carrying the engraving, and usually facing the longer conjugate. In lens drawings, the front generally faces left or up. A notable exception is certain lenses intended to be used in photomicrography in which the front of the lens faces the shorter conjugate.

3.3.6 Back of photographic lens.⁸ The back of a photographic lens, in general, is the end carrying the mounting thread or other attaching means and usually facing the shorter conjugate.

3.3.7 Name of design. Designs of lenses in which particular configurations of elements are employed are often given names. These names are usually trade names, and the name ordinarily applied to any particular configuration is usually the trade name of the oldest design of a particular type such as "Tessar." In some cases, however, the design name may not be a trade name but may be based on some feature of the lens configuration such as "Symmetrical."

3.3.8 Telephoto. A telephoto lens is defined

⁸ American Standard Nomenclature for Parts of a Photographic Lens PHA.25 — 1948.

as a lens for which the telephoto ratio is greater than one. (See 3.1.10.)

3.3.9 Glass types. A constructional feature is the type of optical glass of which each element is made.

3.4 MECHANICAL AND STRUCTURAL FEATURES.

3.4.1 Cell. A cell is a mechanical structure holding an element, component, or member.

3.4.2 Barrel. A barrel is a mechanical structure in which the lens is mounted.

3.4.3 Conc. A cone is defined as the mechanical structure to which a lens barrel or shutter, with lens, is attached in order to bring the image in focus in the film plane of a specific aerial camera.

3.4.4 Lens diaphragm. A lens diaphragm is a mechanical device for reducing the effective aperture of a lens. It may take the form of an iris or a Waterhouse stop. An iris diaphragm consist of leaves providing an opening continuously variable in size. A Waterhouse stop is a removable aperture of fixed size which fits in the lens barrel. Waterhouse stops are usually provided in a graded series of apertures.

3.4.5 Iris diaphragm control. Unless otherwise specified, when looking at the front of a lens or remote control knob, a counter-clockwise rotation of the diaphragm control shall reduce the aperture or stop the lens down.

3.4.6 Parfocalized. Lenses mounted in barrels may be specified as parfocalized, i.e., the flange focal distance may be specified to close tolerances that would secure an image in satisfactory focus when the lenses are interchanged on a camera.

3.4.7 Spanner wrench openings. When required in order to facilitate removal of cells, elements, components, or members from a cell or barrel, there shall be two openings 180 degrees apart for application of a spanner wrench. Each opening shall either be circular in shape, or a slot with parallel sides.

3.5 FIELD OF VIEW. The field of view of a lens is a measure of the size of the image area or conjugate object area which is satisfactorily reproduced. This field may be defined in terms of the maximum size of the negative or projection material with which the lens is to be used.¹⁰ The angular measure for field of view is the half angle, which, unless otherwise specified, is the angle subtended at the first nodal point by the optical axis and a straight line to an object point which is imaged at the extreme corner of the negative. For a projected image, the half angle is the angle subtended at the second nodal point by the optical axis and a line to the image point conjugate with the extreme corner of the projection material. The half angle is sometimes referred to the side of the image area and in such cases it shall always be so specified. The field of view may also be designated as the total field angle which is twice the half angle. Coverage is a less precise term for field of view.

3.6 OPTICAL CHARACTERISTICS. Optical characteristics include all properties of a lens affecting its optical performances such as image quality, distortion, transmittance, image color, and condenser characteristics. When specifying optical characteristics or individual aberrations, the definitions and nomenclature set forth herein shall be used.

3.6.1 Image quality. Image quality em-

¹⁰ Format Sizes for Air Cameras, ABC AIR STD 52/1, 5 Feb. 54. The participants agreed that air camera format sizes shall be: 2¼ by 2¼ inches, 4½ by 4½ inches, 9 by 9 inches, 9 by 18 inches, 18 by 18 inches. Format Sizes for Ground Cameras, ABC AIR STD 52/5, 15 Mar. 54. Ground camera format sizes standardized shall be: 1 by 1¼ inches (24 by 36 millimeters), 2¼ by 2¼ inches, 2.5 by 2.75 inches.

braces all the properties of a lens affecting the quality of the image such as resolving power, aberrations, image defects, and veiling glare. Aberrations are optical defects inherent in the lens design. Because of manufacturing variations, it often happens that the measured aberrations differ from the computed aberrations. Image defects are optical defects not inherent in the lens design and resulting entirely from manufacturing and mounting variations. This standard is primarily concerned with optical performance. Optical performance can be measured in terms of resolving power, or specific optical characteristics.

3.6.2 Resolving power. The resolving power of a lens is a measure of its ability to image closely spaced objects so that they are recognizable as individual objects. The resolving power shall be expressed in lines per millimeter, usually in the short conjugate plane. Resolving power is measured by photographing or observing suitable test charts at specified angular distances from the center of the field. The test charts shall consist of groups of parallel straight lines and spaces of equal width; the resolving power is the reciprocal of the center-to-center distance of the lines that are just distinguishable in the recorded image. By "just distinguishable" is meant that the observer is able to count the correct number of lines in the recorded image, over the entire length of the lines and in the correct orientation, subject to the provision that no coarser pattern shall be unresolved. The appearance of resolution in a finer pattern after failure to resolve a coarser pattern is an indication of the presence of spurious resolution. Spurious resolution is a phenomenon wherein fine lines are resolved, yet coarse lines are not. For non-axial points, it is necessary to consider the orientation of the lines. For example, the resolving power for radial lines, or "radial resolving power" (sometimes called "sagittal resolving power"), at a given point in the

image plane is the resolving power for closely spaced lines that are parallel and adjacent to the radius drawn from the center of the field to the given point. Resolving power for tangential lines, or "tangential resolving power," is the resolving power for closely spaced parallel lines that are tangent and adjacent to a circle drawn through the given point whose center lies at the center of the field. Resolving power may be specified as minimum acceptable resolving power, regardless of whether radial or tangential at specified angles from the optical axis of the lens, or it may be specified at both minimum acceptable radial and minimum acceptable tangential resolving power at specified angular distances from the optical axis. The average resolving power weighted in terms of the area of the negative, the area weighted average resolution (AWAR), provides a single value by which the resolving power for the entire field may be specified. (See 3.1.2.1.1 and 3.6.2.5.)

3.6.2.1 Photographic resolving power. Photographic resolving power is used in specifying and measuring performance of type I, II, III, IV, V, IX, XII, and XIII lenses and is the greatest number of lines per millimeter recorded photographically as separate lines. A target pattern is considered resolved when it meets the conditions described in 3.6.2. Photographic resolving power depends markedly on the photographic conditions employed, and on the presence of background glare from the illuminated target. When specifying photographic resolving power, it is necessary also to specify the color of light to be used, the type of photosensitive material and processing, the lens speed at which the test is made, the contrast of the target, and the magnification or focus at which the lens is tested. (See 5.1.2.12.1.)

3.6.2.2 Visual resolving power. Visual resolving power is used in specifying and measuring of type X lenses, and is defined as the greatest number of lines per milli-

meter in the image of a test target pattern that are just barely distinguishable as separate lines under adequate magnification. When specifying visual resolving power it is necessary also to specify the target contrast. (See 5.1.2.12.2.)

3.6.2.3 Projected photographic resolving power. Projected photographic resolving power is used in specifying and measuring the performance of type VI lenses and is defined as the greatest number of lines per millimeter, in the object plane, that are barely distinguishable as separate lines when observing under magnification a photographically recorded, projected image of a suitable test target. (See 5.1.2.12.3.) When specifying projected photographic resolving power it is necessary also to specify lens speed, focus, magnification, type of illumination, contrast of target, type of photosensitive material and its processing.

3.6.2.4 Projected visual resolving power. Projected visual resolving power is used in specifying and measuring the performance of type VII lenses and is defined as the greatest number of lines per millimeter in the object plane that are distinguishable as separate lines in the projected image. When specifying projected visual resolving power, it is usually understood to imply a high contrast target (dark lines on light background). (See 5.1.2.12.4.)

3.6.2.5 Area weighted average resolution. A single average value for the resolution over the picture format may be determined for any given focal plane as the area weighted average resolution, or AWAR. To determine the AWAR, the picture format is divided into concentric annular zones whose boundaries are determined from the angles which are midway between successive test angles. For zones which extend beyond the boundaries of the picture format, only the area lying within the format shall be used in determining the weighting ratio. The reso-

lution obtained at any given test angle is multiplied by the ratio of the area of the zone for that angle to the total area of the picture format. The AWAR is the sum of these products. To obtain a single value of the resolution for each test angle, the geometric mean of the tangential and radial resolutions shall be used. However, the computations may be simplified by the use of an arithmetic mean whenever the tangential and radial resolutions differ by less than a factor of 2 to 1. When more than one measurement is made at any given test angle, an arithmetic mean shall be determined for the tangential and another for the radial resolutions. The area weighted average resolution is defined as:

$$AWAR = \sum \frac{A_i}{A} \sqrt{R_i T_i} \quad (9)$$

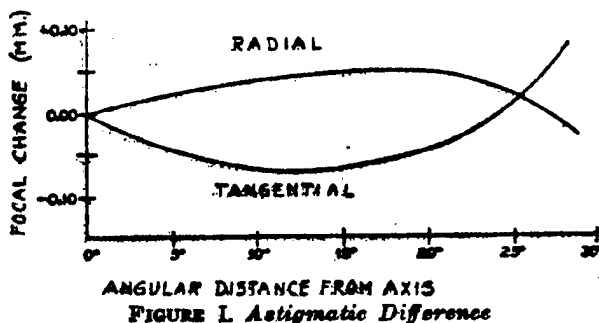
where A_i is the area of a particular zone, R_i is the average radial resolving power in this zone (or radial resolving power at the midpoint of the zone), T_i is the average tangential resolving power in the zone (or the tangential resolving power at the midpoint of the zone), and A is the total area of the picture format, and Σ is the summation sign, summing the values

$$\frac{A_i}{A} \sqrt{R_i T_i}$$

over all zones in the picture area.

3.6.3 Astigmatism and curvature of field. In general, a lens possesses two image surfaces: one in which lines radial to the optical axis are best defined and the other in which lines tangent to circles concentric with the axis are best defined. Noncoincidence of these two image surfaces is called astigmatism, and the separation of the two image surfaces, measured parallel to the optical axis, is called the astigmatic difference. A median surface lying between the two is called the surface of least confusion and the definition in this image surface is least

affected by orientation of the object. None of the surfaces is a true plane. The departure of the surface of least confusion from a true plane is called curvature of field. Resolving power figures, specified in accordance with 3.6.2, will usually be considered as referring to a flat image and object plane. When curvature of field is specified, the magnification at which it is to be measured shall be stated. (See 5.1.2.13.) Figure 1 is plotted as an example of the astigmatic difference.



3.6.4 Color correction. Color correction is defined as the reduction of longitudinal and lateral chromatic aberrations. It may be specified in terms of the kind of light and color sensitivity of the photographic material to be used with the lens, e.g., the lens is color corrected for use with white light and panchromatic film of ASA speed 100. The color correction may be specified in terms of the Fraunhofer lines in the solar spectrum that are to be used in the lens calculations, e.g., C and F correction. The magnification at which the color correction is accomplished shall be designated. (See 5.1.2.14.)

3.6.4.1 Longitudinal chromatic aberration. Longitudinal chromatic aberration is defined as a variation in back focal distance for light of different colors or wave lengths. It is specified in terms of this focal change for light of specified colors. (See 5.1.2.14.1.) Figure 2 is plotted as an example of longitudinal chromatic aberration.

3.6.4.2 Lateral chromatic aberration. Late-

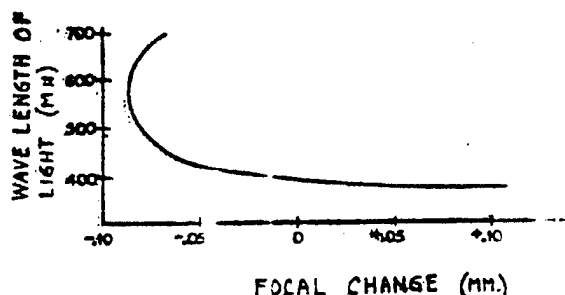


FIGURE 2. Longitudinal Chromatic Aberration

ral chromatic aberration is a variation in image scale of a lens for light of different colors or wave lengths. When required, limits on lateral chromatic aberration will be specified as the radial displacement in millimeters of the image in the first color from the image of the same point in the second color. (See 5.1.2.14.2.) Figure 3 is plotted as an example of lateral chromatic aberration.

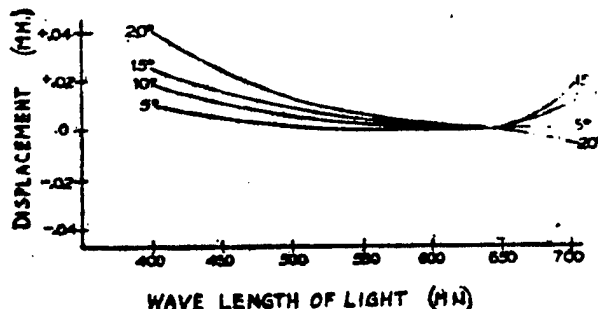


FIGURE 3. Lateral Chromatic Aberration

3.6.5 Magnification.

3.6.5.1 Paraxial magnification. The paraxial magnification, often referred to more simply as magnification, determines the scale of the image when the object is at a finite distance from the lens. The paraxial magnification, or PM, is defined by the following equation:

$$PM = \lim_{\gamma \rightarrow 0} \frac{\gamma'}{\gamma} \quad (10)$$

where γ' is the radial distance from the optical axis to the image point in the image plane

3.8.1 *Material defects.*

3.8.1.1 *Bubbles.* Bubbles are air or gaseous inclusions entrapped within the glass.

3.8.1.1.1 *Seeds.* Seeds are very small bubbles

3.8.1.1.2 *Air bells.* Air bells are irregularly shaped bubbles

3.8.1.2 *Cracks.* Cracks are shallow separations or breaks in the glass.

3.8.1.3 *Feathers.* Feathers are powdered surfaces folded into the glass in the pressing process.

3.8.1.4 *Fold, or laps.* Folds, or laps, are areas in which the glass has been folded upon itself but not fused.

3.8.1.5 *Milkiness.* Milkiness is caused by cloudy or milky areas within the glass.

3.8.1.6 *Stones.* Stones are fragments of undissolved material in the glass.

3.8.1.7 *Strain.* Strain is tension within the glass caused by inadequate annealing or improper mounting. It is an area of index of refraction differing from the nominal.

3.8.1.8 *Striae.* Striae are streaks or veins in the glass with the index of refraction differing from that of the body of the glass.

3.8.1.8.1 *Reams.* Reams are fine bands of striae.

3.8.1.8.2 *Cords.* Cords are streaks of very heavy striae.

3.8.2 *Manufacturing defects.*

3.8.2.1 *Blisters.* Blisters are bubbles in a cement layer.

3.8.2.2 *Burns.* Burns are reddish stains generally ground on the central areas of elements. They are usually caused by the drying-up or glazing of a polisher.

3.8.2.3 *Cement starts.* Cement starts are spots where the components of a cemented lens have started to separate. They can be small irregular spots between the elements or run-ins at the edge, insufficient cement, or cement at the edge dissolved by a solvent.

3.8.2.3.1 *Run-ins.* Run-ins are cement separations at the edge of a cemented component.

3.8.2.4 *Chips.* Chips are areas from which glass has been broken away from the surface, edge, or bevel of an optical element.

3.8.2.5 *Cracks.* Cracks are breaks in the glass.

3.8.2.6 *Digs.* Digs are breaks of the polished surface of a round, oval, square, etc., shape including pits, holes, and surface broken bubbles.

3.8.2.6.1 *Dirt holes.* Dirt holes are digs filled with rouge.

3.8.2.7 *Dirt.* Dirt consists of dust, lint, or other foreign matter on the surface or entrapped in a cement layer.

3.8.2.8 *Grayness.* Grayness is represented by finely ground areas indicating incomplete or improper polishing.

3.8.2.9 *Mold marks.* Mold marks are marks on the surface produced by molding.

3.8.2.10 *Orange peel.* Orange peel is poorly polished surface, pock-marked with pits, having much the same surface appearance as the skin of an orange.

3.8.2.11 *Poor polish.* Poor polish pertains

to polished surfaces containing minute pits of a gray or red color. They are gray grinding pits in the surface of the glass, or red grinding pints in which rouge has been so deeply embedded that it has to be removed by further polishing.

3.8.2.12 Scratches. Scratches are furrows or grooves in the surface of the glass caused by the removal of glass, usually made by coarse grit, fragments of glass, sharp tools, etc., rubbed over the surface.

3.8.2.13 Smears, scum, water spots, etc. Smears, scum, water spots, etc., are residue of evaporated or unevaporated moisture. They are usually removable by "normal" cleaning.

3.8.2.14 Stain. Stain is a discoloration of the glass surface, usually brown, blue, or green, caused by the deposit of foreign matter, or changes produced on the surface of the glass by chemical action of some substance with the glass.

4. GENERAL REQUIREMENTS

4.1 MARKINGS.

4.1.1 Lens markings. Lens markings, such as maximum aperture, focal length, field of view, and serial number shall be placed on the front of the lens cell or on the barrel if space limitations so require. The lens name and serial number shall be assigned by the manufacturer.

4.1.2 Cell marking. Lenses supplied in cells or constructed with removable cells shall have all cells permanently marked with at least the last three digits of the lens serial number.

4.1.3 Maximum aperture. All types of lenses, except types X and XI, shall be marked with their maximum aperture stated either as the relative aperture, aperture ratio or T-stop.

4.1.3.1 The symbol for relative aperture of a lens shall be *f/* followed by the numerical value, for example *f/2.0*.¹²

4.1.3.2 The symbol for the T-stop of a lens shall be T followed by a space and then the numerical value, for example T 2.2.

4.1.3.3 *f*-number.¹² The effective diameter

of the maximum aperture of the lens shall be at least 95 percent of the quotient obtained by dividing the marked focal length by the *f*-number corresponding to the maximum marked aperture.

4.1.4 Iris diaphragm control marking.

4.1.4.1 Full stop.¹² The standard series of diaphragm markings, or stop openings, shall be 0.7, 1.0, 1.4, 2.0, 2.8, 4.0, 5.6, 8, 11, 16, 22, 32, 45, 64, 90, and 128.

4.1.4.2 Maximum aperture value.¹² The *f*-number corresponding to the maximum aperture, T-number, or aperture ratio value marked need not be selected from the above series but shall be followed by the above series of stop openings beginning with the next largest number whenever practical and progressing as far as required in the individual application; e.g., for an *f/1.9* lens the diaphragm might be marked *f/1.9*, 2.8, 4.0, 5.6, 8, etc., if it was believed that to mark it *f/1.9*, 2.0, 2.8, 4.0, 5.6, etc., would confuse the marking at the *f/1.9* end of the scale.

4.1.4.3 Fractional stop values. In addition to the numbered values, each stop may be divided into three subdivisions by dots or marks (not numbered), the dots being at "thirds of a stop," e.g., 0.7, 0.8, 0.9, 1.0, 1.12,

¹² American Standard Lens Aperture Markings, Z39.4.7-1938.

solving power target used on all tests shall be as follows: The target shall consist of a series of patterns decreasing in size as the $\sqrt{2}$, $\sqrt[3]{2}$, $\sqrt[4]{2}$, with a range sufficient to cover the requirements of the lens-film combination under test. The standard target element shall consist of two patterns (two sets of lines) at right angles to each other. Each pattern shall consist of three lines separated by spaces of equal width. Each line shall be five times as long as it is wide. (See Figure 7.) For types I and II lenses, targets with light lines on a dark background are preferred; for types IV, VI, VII, XII, XII lenses, targets with dark lines on a light background are preferred. The target contrast (the difference in photographic density between the lines and spaces) shall be either high, medium, or low contrast, as specified.

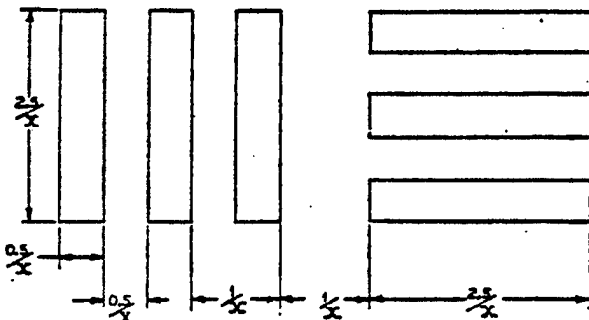


FIGURE 7. Standard Resolving Power Test Target Element. The patterns of lines are parallel lines 2.5 x millimeters long and 0.5 x millimeters wide with space 0.5 x millimeters wide between the parallel lines, where x equals the numbers of lines per millimeter.

5.1.1.7.1 High contrast target. A high contrast target is one in which the density difference between the light and dark areas is greater than 2.00.

5.1.1.7.2 Medium contrast target. A medium contrast target is one in which the density difference between the light and dark areas is equal to 0.80 ± 0.05 .

5.1.1.7.3 Low contrast target. A low contrast target is one in which the density dif-

ference between the light and dark areas is equal to 0.20 ± 0.05 .

5.1.2 Test methods.

5.1.2.1 Plane of best definition. The plane of best definition is usually determined by making a series of evaluations at a sufficient number of focal settings. The distance between focal settings in hundredths of millimeters shall be at least

$$\frac{\text{f-number of lens}}{\text{no. of lines/mm. expected}}$$

The detailed specification shall state the method used in determining the plane of best definition.

5.1.2.2 Equivalent focal length.

5.1.2.2.1 Method 1 — Photographic method.¹⁴ The EFL shall be measured by placing a photographic plate in the focal plane of the image space. Unless otherwise specified, the focal plane is defined as the place of best photographic imagery for an infinity distant axial point; the focal plane may also be specified as the plane of best definition. A collimator and reticle may be conveniently used to provide an infinitely distant object point. Exposures are made with the beam of light from the collimator directed along the optical axis of the lens and a series of angles β_1, β_2 , etc. On the resultant negative, measurements shall be made of the distances γ_1, γ_2 , etc., from the axial images to the images corresponding to the angles β_1, β_2 ,

etc., and the quotient
$$\frac{\gamma_1}{\tan \beta_1}, \frac{\gamma_2}{\tan \beta_2}$$

etc., formed. The limiting value of this quotient as β approaches zero is the EFL. In a photographic objective free from distortion, the quotient is invariant with respect to the

¹⁴ American Standard Methods for Designating and Measuring Focal Lengths and Focal Distances of Photographic Lenses, Z38.4.21-1948.

value of β . For many photographic purposes the distortion is negligible for points distant from the center of the useful field not more than one-fifth of its radius, and consequently, it will very often be possible to obtain a satisfactorily accurate value of the EFL by a single determination of β and γ' for a point lying near the axis.

5.1.2.2.1 Method 1A — Combination method. The EFL also may be determined by adding the photographic BF to the distance from the rear vertex to the emergent nodal point. The latter distance may be determined by Method 2.

5.1.2.2.2 Method 2 — Nodal slide method. The lens to be tested shall be mounted on a nodal slide to rotate about the vertical axis through its second nodal point. The distance from this nodal point to the position of best axial focus for an infinitely distant object point shall be measured. This is also known as the second principal focus. (An important factor or uncertainty in using this method is the difference between the position of best focus as judged visually on the optical bench and the best focus as determined photographically by method 1.) When using this method, the criterion for determining the best axial focus should be specified. The criterion used is dependent on the type of test object or target used and may be specified in terms of either the haze position or the position of greatest concentration (see 3.6.9.1.1 and 3.6.9.1.2) or in terms of the color in and around the image.

5.1.2.3 Calibrated focal length. When determining the calibrated focal length, the plane of best average definition shall be chosen as the focal plane. To compute the calibrated focal length, let γ'_1 , γ'_2 , etc., represent the distances in the focal plane from the axial point to the images of infinitely distant object points lying in the directions making angles β_1 , β_2 , etc., with the optical axis of the objective. If f is the equivalent

focal length in the absence of distortion, then

$$\gamma'_1 = f \tan \beta_1 \quad (13)$$

$$\gamma'_2 = f \tan \beta_2$$

$$\text{and } \gamma'_0 = f \tan \beta_0 \quad (14)$$

In the presence of distortion

$$\gamma'_1 = f \tan \beta_1 + \Delta' \gamma'_1 \quad (15)$$

$$\gamma'_2 = f \tan \beta_2 + \Delta' \gamma'_2$$

$$\text{and } \gamma'_0 = f \tan \beta_0 + \Delta' \gamma'_0 \quad (16)$$

The added terms are the values of the linear distortion for values β_1 , β_2 , etc., respectively. The values of γ' and β are measured directly. It is evident that the individual values of the distortion defined by the above group of equations can be changed by changing the value of f . If f is the equivalent focal length, in many instances values of the distortion in the neighborhood of the axial image point will be small, and near the edge of the field the values will be large and predominantly negative or positive. Infinitely distant targets may be provided by a group of collimators or by one collimator which can be successively placed in the required angular positions. Exposures shall be made and the γ' corresponding to each angular distance from the optical axis shall be determined.

5.1.2.4 Back focal distance.¹⁵ To determine the BF, the focal plane in the image space shall be determined by a visual or photographic method. The measured distance from this focal plane to the vertex of the back surface of the lens shall be the required BF.

5.1.2.5 Flange focal distance.¹⁵ To determine the FD, the focal plane in the image space shall be determined by a visual or photographic method. The measurement shall be made from the plane of the locating surface or the flange to the focal plane.

5.1.2.6 Front focal distance.¹⁵ To determine the FF, the focal plane in the object space shall be determined by a visual or

¹⁵ See footnote 14, page 21.

photographic method. The measured distance from this focal plane to the vertex of the front surface of the lens shall be required FF.

5.1.2.7 Front vertex back focal distance. To determine the FVD, the focal plane in the image shall be determined by a visual or photographic method. The measured distance from the vertex of the front surface of the lens to the focal plane shall be the required FVD.

5.1.2.8 Aperture ratio. For the special case in which the object is at infinite distance (magnification = 0), N , the first member of the ratio equation (2) in 3.2.2, may be determined as the quotient obtained when the EFL is divided by the diameter of the effective aperture.

5.1.2.8.1 For the general case in which the magnification may have any value, a pinhole should be mounted at the axial point of the desired image plane, and the angle of the cone of light emerging through the pinhole from the lens should be determined by measuring the diameter of a right section of the cone at a suitable distance beyond the pinhole. The angle α can be calculated from the measurements and substituted in equation (2). If n is the index of refraction of the medium in which the angle α is measured ($n = 1$ for air, used in the great majority of cases), the second member of the

aperture ratio is
$$\frac{2n \sin \alpha}{1}$$

When measuring the aperture ratio by the method of this paragraph, the angular subtense of the object point at the first nodal point of the photographic objective must be small as compared with the value of the angle α between the optical axis of the objective and the extreme ray proceeding to the image point.

5.1.2.9 Effective aperture.

5.1.2.9.1 Method 3 — Microscope method.¹⁶ A traveling compound microscope is required with means for translating the microscope in a direction at right angles to its optical axis through a measured distance not less than the diameter of the maximum effective aperture to be measured. The microscope must be of low power (10X to 20X) provided with a reticle and with a working distance sufficiently long to permit the microscope to be focused on the limiting opening of the photographic objective through the front member. The photographic objective, of which the effective aperture is to be measured, shall be mounted in a convenient position to permit the traveling microscope to be directed parallel to the optical axis of the objective and focused upon the edge of the opening having the smallest apparent diameter. (The photographic objective is not to be disassembled.) This edge shall be viewed through the lens elements which are normally traversed by image-forming light before passing through the limiting opening. A microscope having a long working distance is required to avoid mechanical interference when looking through the lens elements. A microscope shall then be traversed and measurements made to determine the apparent diameter of this opening which shall be the effective aperture. In place of a traveling microscope, a suitable contour projector may be employed to measure the effective aperture. If the lens has a non-circular aperture, the measured diameter must be suitably corrected.

5.1.2.9.2 Method 4 — Point source method.¹⁷ When it is not practicable to use a microscope of sufficient working distance to permit the limiting opening to be observed through the lens elements, a source of light, as small as practicable and emitting a cone sufficiently large to fill the lens, may be

¹⁶ American Standard Methods of Designating and Measuring Apertures and Related Quantities Pertaining to Photographic Lenses, Z38.4.20-1948.

¹⁷ American Standard Aperture Calibration of Motion Picture Lenses, PH22.90 — 1953.

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placed at the second principal focus and directed toward the objective; the diameter of the emergent beam should be measured as near the front of the objective as is practicable. This method is subject to a systematic error, the value of the finite size of the source.

5.1.2.10 T-number and transmittance. The equipment specified in methods 5 and 6 for determining T-stops and transmittance of a lens represents workable apparatus. However, modifications are permitted provided that the basic requirements of the method and the specified accuracy are met. (See 3.2.6 and 4.1.4.4.)

5.1.2.10.1 Method 5 — Extended source method.¹⁸ This method of lens calibration is based on filling the lens with light from an extended uniform source of adequate size and placing in the plane of best definition of the lens a metal plate with a hole, the diameter of which shall not exceed 3 millimeters (or 1.5 millimeters for 8-millimeter film), at its center. The light flux passing through the hole shall be measured by a photocell arrangement. This flux shall then be compared with the flux passing through a hole of the same dimensions from an open circular aperture of such a size and at such a distance from the plate that it subtends the desired angle α so that $\sin \alpha = \frac{1}{2} T$, where T is the T-number to be measured. The greatest care is necessary to insure that the extended source is uniform. In practice, the photocell reading for each whole T-number is first determined for a series of open apertures at a fixed distance from the plate. The lens is then substituted for the open aperture with the 3-millimeter hole accurately in its focal plane and the iris of the lens closed down until the photocell meter reading produced by the lens is equal to each of the successive open hole

readings. The full T-stop positions are then marked on the diaphragm ring of the lens. The intermediate thirds of stops may be found with sufficient accuracy by inserting a neutral density filter of 0.1 and 0.2 behind each open aperture in turn and noting the corresponding photocell readings or by dividing the travel of the diaphragm control into three equal parts. The extended source should be uniformly bright over its useful area to within ± 3 percent. (This could be tested with a suitable telephotometer, or a small hole in an opaque screen could be moved around in front of the source and any consequent variations in photocell reading noted.) The source may be a sheet of ground glass covering a hole in a whitelined box containing several lamps mounted around the hole and shielded so that no direct light from the lamps falls on the ground glass itself. The photocell receiver may be of the phototube type with a simple d-c amplifier. Care must be taken to insure that phototube sensitivity does not change between marking readings on the open aperture and on the lens itself. To guard against this, some turret arrangement is desirable, with the lens on one side and the open aperture on the other, so that the two may be interchanged and compared quickly with each other by turning the turret. Transmittance of a lens shall be measured at the maximum relative aperture in a direction parallel to the optical axis of the lens. Transmittance is equal to C/R where C is the calibrated photocell reading with the lens in place, and R is a similar reading when a clear circular aperture is in place, subtending an angle α at the hole in the front of the photocell so that $\sin \alpha = \frac{1}{2} N$, where N is the second term in the aperture ratio of the lens to be tested. (See 3.2.2.) The value of N must be the true value, which may differ from that indicated on the barrel.

5.1.2.10.2 Method 6 — Collimator method.¹⁹ In this method, light from a small

¹⁸ See footnote 17, page 22.

¹⁹ See footnote 17, page 22.

source (a 5-millimeter hole covered with opal glass and strongly illuminated from behind) shall be collimated by a simple lens, or an achromat if preferred, of a focal length at least three times the EFL of the lens being tested and of sufficient aperture to fill the lens being calibrated. This gives a collimated beam which will be focused by the test lens to form a small circle of light in its focal plane. This circle of light will be less than the prescribed limit of 3 millimeters diameter. Uniformity of the collimated beam can be checked by moving a small hole in an opaque screen across the beam, and noting any variations in the photocell reading. For the comparison unit, an open aperture shall be used, of diameter equal to the focal length of the lens divided by the desired T-number. This aperture shall first be mounted in front of an integrating sphere of adequate size with the usual photocell detector and the light from the collimator allowed to enter the aperture. The aperture plate shall then be replaced by the lens, the iris diaphragm closed down to give the same photocell reading, and the T-number engraved on the iris ring. The intermediate thirds of stops can be found by using 0.1 or 0.2 density filters, or by dividing the travel of the diaphragm control into three equal parts. To guard against "drift" or line-voltage variations which might occur between readings of the comparison aperture and the lens, it is convenient to leave the known standard aperture in place in front of the sphere, and to insert the lens into the beam in such a position that the small image of the source falls wholly within the standard aperture. The meter reading should then remain the same with the lens in or out of the beam. A second plate with a 3-millimeter aperture should be placed over the comparison aperture while the lens is in place to stop any stray light which may be reflected from the interior of the lens. It should be noted particularly that if this method is used, the focal length of the lens must be

measured separately and a suitable set of open apertures constructed for use with it. However, by suitable devices, one single set of fixed apertures may be used for all lenses. Transmittance of a lens shall be measured at the maximum relative aperture in a direction parallel to the optical axis of the lens. Transmittance is equal to C/R where C is the calibrated photocell reading with the lens in place, and R is a similar reading when a clear diaphragm (equal to the lens effective aperture) is in place.

5.1.2.11 *Relative illumination.*

5.1.2.11.1 *Method 7 — Extended source method.* This method of measuring relative illumination makes use of the same apparatus and techniques specified in method 5. With the lens to be measured set up in the apparatus, the photocell shall be displaced laterally to the position corresponding to the required angular positions, and the corresponding percentage of axial illuminance for each position is found from a calibration curve of the photocell meter.

5.1.2.11.2 *Method 8 — Collimator method.* This method of measuring relative illumination makes use of the same apparatus and techniques specified in method 6. With the lens to be measured set up in the apparatus, the lens shall be rotated through the desired field angles β and the photocell readings compared with the readings for the lens on axis. The percentage of light flux transmitted can then be read off a calibration curve for the photocell system and converted to desired percentage illuminance by dividing by $\cos^3 \beta$.

5.1.2.11.3 *Method 9 — Densitometric method.* This method of measuring relative illumination makes use of the same apparatus and techniques as specified in methods 5 and 6, except that a photographic plate is substituted for the photocell when the extended source is used, and for the integrating sphere

when a collimator is used. In the latter case, the image produced by the lens should be in sharp focus on the emulsion plane. The exposures are made on the axis and at the required angular positions off axis. The exposure times shall be the same at all the positions. The densities of the exposed and developed images shall be measured and the relative illuminance determined using the sensitometric curve of the emulsion, obtained by exposing a calibrated step-wedge.

5.1.2.11.4 Method 10 — Indirect computation method. The indirect computation of illuminance distribution from dimensions of the lens are outlined in this section. The method in this case is for a lens while in the design stages, or in determining the illuminance distribution of an actual lens when no convenient photometric equipment is available.

5.1.2.11.4.1 Distortionless lens with object at infinity. The case where the object is at infinity is applicable to most photographic objectives encountered in aerial and ground photography. The field angle of such a lens is always expressed by the obliquity angle ϕ , in the object space. The desired relative illumination is given by:

$$R = \frac{E_{\phi}}{E_0} = \frac{S_{\phi}}{S_0} \cos^4 \phi \quad (17)$$

where E is the illuminance at the point in the image which corresponds to the obliquity angle ϕ in the object space, and E_0 is the illuminance at the center of the field. S_{ϕ} and S_0 are, respectively, the beam section areas of the oblique and axial beams at the chosen reference plane in the object space. The area S_{ϕ} will in general be smaller than S_0 due to vignetting, but in some unusual lenses, S_{ϕ} may be somewhat greater than S_0 .

5.1.2.11.4.2 Distortionless lens with finite object distance. The relative illumination R can be computed either in the object space

or in the image space depending on which is more convenient. The illuminance at angle ϕ is given by the integral:

$$E_{\phi} = K \int \cos^4 \phi dS = K' \int \cos^4 \phi' dS' \quad (18)$$

where K and K' are constants independent of obliquity. The integrals are to be taken over the respective beam sections. The integrals are necessary because ϕ and ϕ' vary from point to point over the beam sections. If the aperture is small, the integral becomes unnecessary and then:

$$E_{\phi} = K S_{\phi} \cos^4 \phi = K' S'_{\phi} \cos^4 \phi' \quad (19)$$

The relative illumination is then found by evaluating E_{ϕ} and E_0 for an oblique and axial beam and taking the ratio $R = E_{\phi} / E_0$.

5.1.2.11.4.3 Distorting lens with object at infinity. This differs from the previous case because the distortion will have a considerable effect on the distribution of illuminance expressed as a function of the entering obliquity angle ϕ . In this case the relative illumination becomes:

$$R = \frac{E_{\phi}}{E_0} = \frac{S_{\phi}}{S_0} \cdot \frac{f^2 \sin \phi \cos \phi}{h' (dh'/d\phi)} \quad (20)$$

S_{ϕ} and S_0 are the areas of the beam sections for the oblique and axial beams at the chosen reference plane in the object space; ϕ is the obliquity angle in the object space, f is the focal length of the lens and h' is the image height. By measurements or computations on the lens, a relation can be established connecting h' with ϕ , from which the value of the derivative $dh'/d\phi$ can be found at any desired point in the field. For a distortionless lens, $h' = f \tan \phi$; in that special case equation, (20) simplifies to equation (17).

5.1.2.11.4.4 Distorting lens with finite object distance. The image space equations (18) or (19) hold independent of the distortion of

the lens. If it is desired to use the data of the object space, equation (18) becomes:

$$E\phi = K \frac{h}{h' (dh') (dh)} \int \cos^4 \phi \, dS \quad (21)$$

where K is a constant different from that used in equation (18). h is the object height, and h' the height of the image of that object. The derivative dh'/dh must be found by determining an algebraic relationship between h and h'. If the aperture is sufficiently small, ϕ will not vary greatly over the beam section and the equation may be reduced to the approximate form.

$$E\phi = K \frac{h}{h' (dh') (dh)} S\phi \cos^4 \phi \quad (22)$$

5.1.2.11.4.5 *Monocentric lens.* In the case of a lens having a common center of curvature to all the surfaces and a concentric image surface, the relative illumination contains only one cosine, namely:

$$R = \frac{E\phi}{E_0} = \frac{S\phi}{S_0} \cos \phi \quad (23)$$

5.1.2.12 *Resolving power.* When specifying or measuring resolving power, care should be taken to consider the following pertinent factors: methods of tests, contrast of target used, kind of and processing of photo-sensitive emulsion, whether filter is to be used, and magnification at which resolving power target images are read. For reading resolution, a magnification of the lowest power which permits convenient viewing will yield the highest resolution readings. (The rule based on Selwyn's experiments²⁰ that

the numerical value of the magnification should equal the number of lines per millimeter expected to be resolved can be considered a rule of thumb.)

5.1.2.12.1 *Photographic resolving power.* When conducting photographic resolving power tests by methods 11 and 12, the photo-sensitive material and processing should be in accordance with table II.

5.1.2.12.1.1 *Method 11 — Collimator method.*²¹ For lenses primarily intended for use on distant objects, such as types I, II, III, and V, this method should be used. The resolving power target is placed at the principal focus of a collimator and illuminated with white light. A filter of a specified color may be used and it shall be placed between the light source and the target. It is recommended that, in order to eliminate vibration effects, a flash discharge lamp be used as the light source and that the light from it be filtered if necessary to approximate white light. (See 5.1.1.4.) Exposure can be controlled by means of neutral density filters between the light source and the target. The lens to be tested shall be placed in the collimated beam from the target and a test plate or film made in a series of focal settings as described in 5.1.2.1. Unless otherwise specified, the lens shall be set at the specified maximum relative aperture. With the test plate perpendicular to the optical axis of the lens, exposure shall be made of the test target at the specified angular distance from the axis out to and including the multiple of the specified angle falling nearest the corner of the plate inside the picture format. The specified angle should be multiples of $1\frac{1}{4}$ degrees and should be spaced to provide 5 increments or more in the semi-field of the lens. The exposure time shall be the same for all angular settings and shall be the

²⁰ E. W. Selwyn, National Bureau of Standards C624, 219, 1964 and Photographic Journal 53B, 46, 1948.

²¹ In method 11, if the resolving power is measured by rationing from the lines per millimeter of the target, EFL of the collimator, and EFL of the test lens, the value should be corrected by multiplying radial lines by the cosine of the field angle and tangential lines by the \cos^2 of the field angle.

TABLE II

Lens type	Photosensitive material	ASA Exposure index	Development (gamma)
I (70-mm. format & smaller)	Panchromatic aerial	10	2.0 ± 0.10
(5-inch format & larger)	Panchromatic aerial	80	1.5 ± 0.10
II (70-mm. format & smaller)	Panchromatic aerial	10	2.0 ± 0.10
(5-inch format & larger)	Panchromatic aerial	80	1.5 ± 0.10
III	Panchromatic aerial	50	0.8 ± 0.10
IV	Panchromatic microfilm	Maximum contrast
V	Panchromatic (motion picture)	50-80	0.8 ± 0.10
IX	Panchromatic (portrait)	100	0.6 ± 0.10
XII	Panchromatic microfilm	Maximum contrast
XIII	Panchromatic microfilm	Maximum contrast
XIV	Blue sensitive recording	1.5 ± 0.10

exposure time which gives the highest resolving power at the angular setting nearest the angle equal to one-half the half angle of view. The different angular settings may be obtained by moving the lens and test plate about an axis near the entrance pupil or by moving the collimators, or by means of a series of collimators placed in the correct angular positions. The lens may be tested with or without the filter provided with it, as required.

5.1.2.12.2 Method 12 — Target range method. For lenses primarily intended for use at finite distances, such as types IV, XII, and XIII, this method should be used. Also, it may be used, when specified, for testing other types of lenses. Properly illuminated high contrast resolving power targets shall be placed in the object space in a plane perpendicular to the optical axis of the lens to be tested and spaced at the required angular distances. The distance from the lens to the plane of the targets shall be designated. When this method is used for testing lenses at infinity focus, either formula (12) in 5.1.1.3 may be used to determine the proper distance, or some designated distance may be used. The test plate shall be adjusted per-

pendicular to the optical axis of the lens and exposed for maximum resolution at the target nearest the angle equal to one-half the half angle of view of the lens being tested and shall be moved in a series of focal settings as described in 5.1.2.1. The sensitized material, processing, etc., shall be in accordance with table II.

5.1.2.12.2 Method 13 — Visual resolving power. When visual resolving power measurements are required (such as type X lenses), they will be made exactly like the photographic resolving power tests, except that the aerial image, when it is real and easily available, will be observed visually under magnification. Method 11 or 12 in 5.1.2.12.1 will be used as specified, depending on the use of the lens. When the image formed by a viewfinder (type X lens) is a virtual image, a telescope stopped down to 5 millimeters and placed at the eye position will be used to observe the image. In this case, the resolution shall be determined in terms of a specified test chart at a specified distance. In all cases where the image is formed on a ground glass, the ground glass shall be removed to observe the aerial image, and the image shall be observed on a plane.

addition of this step enables one to measure prism angle. When measuring distortion at finite distances the plane of the targets must be parallel to the test plate. Mathematical means for adjusting the measurements may be used to eliminate error from this source. If the distortion is to be measured for an object at a finite distance, the targets shall be set up at the required distance as specified. The test procedure is the same as for the object at infinity, except that the distortion is determined on the basis of paraxial or calibrated magnification.

5.1.2.16.2 Method 26 — Collimator bank method. This method is intended for use with lenses mounted either in cameras or in test barrels. Method 26 is similar to method 25, except that a bank of collimators containing targets shall be used instead of a target range.

5.1.2.16.3 Method 27 — Single collimator photographic method. In some cases where high precision is not required, a single collimator may be used in conjunction with a test plate as in method 26. In this method, either the collimator or the lens and the test plate shall be rotated through the required field angles about the center of the entrance pupil of the lens.

5.1.2.16.4 Method 28 — Nodal slide method. This is a visual test method and may be used, when specified, for lenses mounted in barrels. The lens to be tested shall be properly placed on the nodal slide of an optical test bench and centered so that its optical axis is nearly coincident with the axis of the microscope. Distortion for a particular angle shall be measured by the lateral displacement of the observing microscope required to center the target at each angular setting. At each angle β , the microscope shall be displaced along its horizontal axis by the distance $f(1 - \cos \beta) / \cos \beta$ away from the lens. This refocusing is not necessary if a flat field bar is used. To obtain the value of distortion,

the lateral distance through which the microscope shall be displaced must be divided by the cosine of the angle at which the distortion is being measured. Because of inaccuracies present in most optical benches, it is desirable to make each measurement at the same indicated angle on each side of the axis and to average the two microscope readings obtained before computing distortion.

5.1.2.16.5 Method 29 — Goniometer method. This is a visual method intended for use with lenses mounted in cameras. An accurately calibrated test object on glass, usually in the form of a scale or grid, shall be placed in the plane of best definition of the lens to be tested and illuminated in a direction toward the lens to be tested. This test object must be flat, properly centered, and perpendicular to the optical axis. The lens and illuminated test object shall be placed in the goniometer so that the axis about which the angles are measured passes through the center of the entrance pupil of the lens. The telescope of the goniometer shall be pointed at successive points on the test object and the field angles determined. (The telescope shall not be refocused during the run of measurements.) From the focal length of the lens being tested and the calibration of the test object, the angles subtended by the various points on the test object can be computed. Distortion then can be computed in terms of the difference in angles on the object side and image side; this distortion in turn can be converted into the standard form. (See 5.1.2.3.) By adjusting the focus of the telescope, this method can be expanded to include some cases in which the test object is in a plane corresponding to some finite magnification. Care should be exercised to insure that the cone of light from the test lens is included in the entrance pupil of the telescope.

5.1.2.16.6 Method 30 — Projection method. This method is intended primarily for testing projection lenses. A test object simi-

lar to the one used in method 29 shall be placed in the object plane of the lens to be tested and projected onto a suitable screen. Measurements shall be made of the projected image of the test object. The distortion shall be computed in terms of the test object. Care should be taken to insure that the screen and test object are perpendicular to the optical axis of the lens and that the test object is flat and properly centered. The cone of light from the projection lamp shall completely fill the projection lens, and the test object shall be uniformly illuminated. The sign of distortion is reversed from theory on projection through a lens and measured at the long conjugate.

5.1.2.16.7 Tangential distortion. Any of the six methods for measuring radial distortion may be modified to measure tangential distortion by considering the displacement of image points perpendicular to a radius from the center of the field. The magnitude of tangential distortion varies from zero along one diameter to a maximum along an orientation 90 degrees to the diameter of zero distortion. Therefore, when required, tangential distortion shall be measured for two axial orientations of the lens, and the orientation of maximum tangential distortion computed.

5.1.2.17 Prism effect. To measure the prism effect in terms of a thin equivalent prism of vertex angle α , use is made of the fact that oblique rays are deviated by the prism more than, and in the same direction as, the axial ray. An assumption is made that the axial ray makes only a small angle with the normal to the surface of the prism (or the prism may be assumed to be in the minimum deviation for the axial ray). If the camera under test is used to photograph three collimators or distant targets, one axial and the other two making angles $+\beta$ and $-\beta$ with the axis, the distances from the 0 degree image to the $+\beta$ image and from the 0 degree image to the $-\beta$ image

are different in the presence of a prism effect. This difference is measured on the negative. Under the assumptions made, the analytical expression for this difference is:

$$\Delta = f[\tan(\beta + \epsilon) - \tan(\beta - \epsilon) - 2 \tan \epsilon_0] \quad (26)$$

where f is the equivalent focal length of the lens, ϵ is the deviation of the ray making β with the axis (within a close approximation the deviation is the same for $+\beta$ and $-\beta$), and $\epsilon_0 = \alpha/2$ is the deviation of the axial ray. Tables for Δ can be computed for various values of f , β , and α . The measured and tabulated values of Δ are compared, and the corresponding α is evaluated.

5.1.2.18 Spherical aberration.

5.1.2.18.1 Method 31 — Annual ring or Hartmann disk method. When spherical aberration is specified in terms of change in focal position for zones of different radii, a Hartmann disk (a plate covering a front of the lens with holes at the different zones) or aperture consisting of open annular rings will be placed over the front of the lens and properly centered. Either a photographic or visual method of determining the difference in focal positions for different zones may be used. Various modifications of these methods and other methods may be employed, such as a knife-edge test or interferometric method. When measuring spherical aberration for an object at infinity, the target which is imaged by the test lens may be placed in a collimator or a distance at least 25 times the focal length of the lens to be tested.

5.1.2.18.2 Method 32 — Stopped-aperture method. When spherical aberration is specified in terms of the difference between the best focus at maximum aperture and at a designated reduced aperture, a nodal slide optical bench or an autocollimation method may be used to determine the difference in

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